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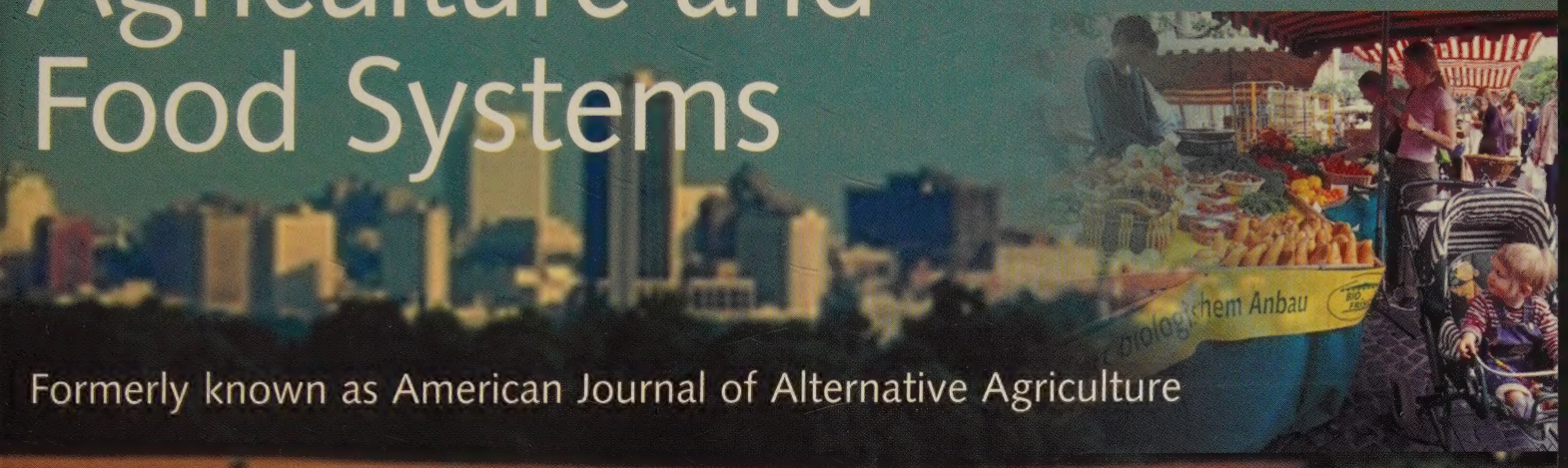

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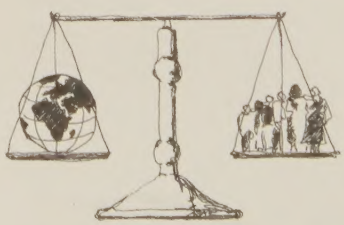

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Introduction of floating gardening in the north-eastern wetlands of Bangladesh for nutritional security and sustainable livelihood

Haseeb Md. Irfanullah[1,*], Ahana Adrika[1], Abdul Ghani[2], Zakir Ahmed Khan[3], and Md. Abdur Rashid[2]

[1]The World Conservation Union (IUCN), Bangladesh Country Office, House 11, Road 138, Gulshan 1, Dhaka 1212, Bangladesh.
[2]Environment and GIS Unit, SHOUHARDO Program, CARE Bangladesh, Pragati RPR Center, 20-21, Karwan Bazar, Dhaka 1215, Bangladesh.
[3]Kishoreganj Regional Office, SHOUHARDO Program, 452 Nilganj Road, Sholakia, Kishoreganj 2300, Bangladesh.
*Corresponding author: hmirfanullah@yahoo.co.uk

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Abstract

Floating gardening is a form of hydroponics or soil-less culture. It is an age-old practice of crop cultivation in the floodplains of southern Bangladesh, where aquatic plants such as water hyacinth (*Eichhornia crassipes*) are used to construct floating platforms on which seedlings are raised and vegetables and other crops cultivated in the rainy season. The platform residue is used in the preparation of beds for winter vegetable gardening. Floating gardening was introduced in 2006 on a pilot-scale in the north-east wetlands of the country, as a contribution to food security and as a supplementary income for the marginalized community. The overall experience of floating cultivation in three selected villages was encouraging. Local people became aware of this new farming system and their level of knowledge improved. Communities were mobilized into groups to make floating platforms, and platform residues were later used to establish winter gardens. Cultivation was successful on both types of plot, and vegetables were both consumed by the producers and sold in the market. The input–output analysis revealed floating gardening to be a feasible alternative livelihood option for the wetland dwellers. The method provided targeted landless people with parcels of land in the monsoon, enabling them to grow vegetables. Floating gardening and associated winter gardening appear to have the potential for introduction to other parts of the world where aquatic weed management is a major problem.

Key words: homestead gardening, food security, natural resources, weed control, wetlands

Introduction

Floating gardening is an ancient practice of crop cultivation in the floodplains of the southern parts of Bangladesh (e.g. Gopalganj, Barisal and Pirojpur Districts)[1]. This form of hydroponics, or soil-less culture is comparable with cultivation techniques practiced in several parts of the world, e.g. by the Aztecs in Central America, in Kashmir in India and in southern Myanmar. In Bangladesh, plants, mostly aquatic, are used to construct thick, floating platforms on which seedlings are raised, and vegetables and other crops are cultivated in the monsoon (Fig. 1). In addition, the platform residue is used for winter vegetable gardening in preparation of beds or as bio-fertilizer. Floating gardening is known as *baira*, *boor*, *gathua*, *geto*, *daap* and *gatoni* in different parts of Bangladesh. Water hyacinth (*Eichhornia crassipes*) is the major component of floating garden platforms since it is one of the most common aquatic plants of the wetlands of Bangladesh[1,2].

Bangladesh is a land of water and wetlands. The wetland ecosystems are very important to the economy and lives of the people of the country, as their livelihoods and subsistence are very much linked with the productivity of wetlands. One important type of wetland in Bangladesh is

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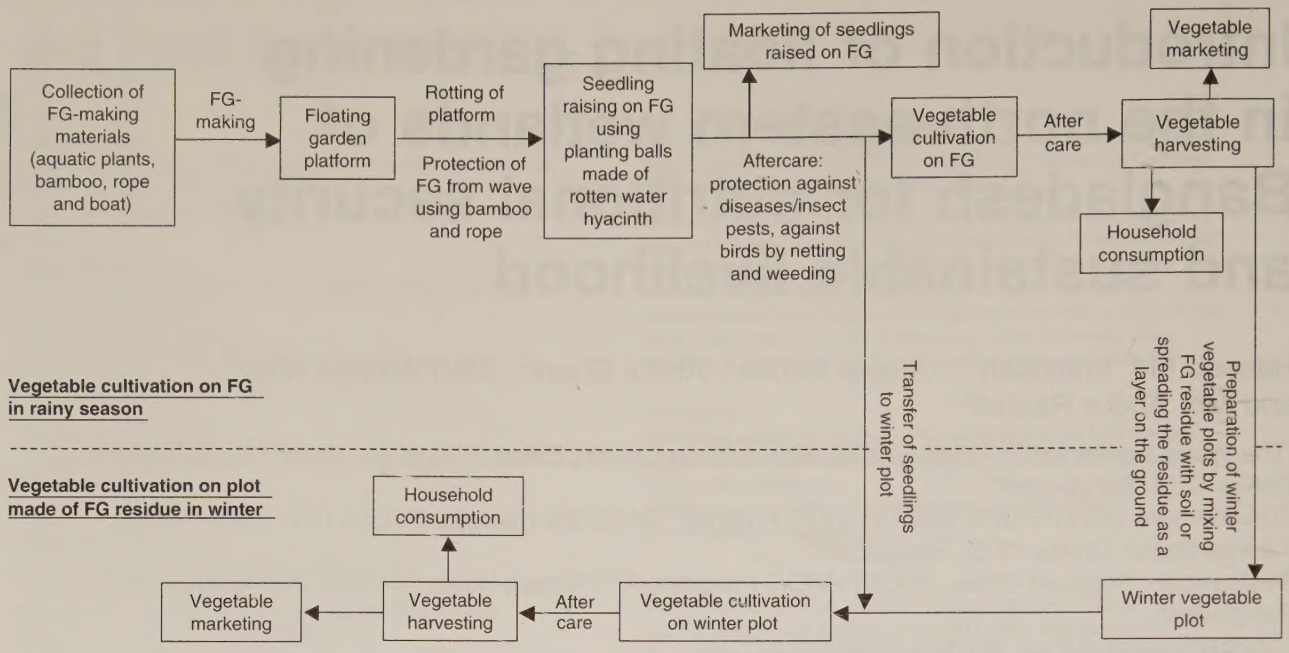
Collection of FG-making materials (aquatic plants, bamboo, rope and boat)
FG-making
Floating garden platform
Rotting of platform
Protection of FG from wave using bamboo and rope
Seedling raising on FG using planting balls made of rotten water hyacinth
Marketing of seedlings raised on FG
Aftercare: protection against diseases/insect pests, against birds by netting and weeding
Vegetable cultivation on FG
After care
Vegetable harvesting
Vegetable marketing
Household consumption
Transfer of seedlings to winter plot
Preparation of winter vegetable plots by mixing FG residue with soil or spreading the residue as a layer on the ground
Vegetable cultivation on FG in rainy season
Vegetable cultivation on plot made of FG residue in winter
Household consumption
Vegetable marketing
Vegetable harvesting
After care
Vegetable cultivation on winter plot
Winter vegetable plot

Figure 1. Flow-chart showing floating gardening and winter vegetable gardening traditionally practiced in Bangladesh (FG, floating garden).

haor, which is a large back swamp or bowl-shaped depression located between the natural levees of rivers, and usually consisting of a number of saucer-shaped depressions that retain water all year around. The haor areas of north-east Bangladesh are characterized by prolonged flooding, for about seven or eight months each year. The lack of cultivable land restricts agricultural activities to just the few dry months of winter. Lack of employment, and migration to other areas during the rainy season are common practices in the haor area. If a cultivation technique could be introduced to overcome the want of agricultural space in the rainy season, it would be likely to have an important beneficial influence on livelihoods.

Against this background, floating gardening could be considered as an important tool for poverty alleviation and food security for the people living in haor areas. This environment-friendly agriculture system can create local jobs in the wet season when job opportunities are limited, and it provides a use for the stagnant water that would otherwise remain unused during the monsoon. The technique can also increase the land-holding capacity of poor, landless people, who will be able to grow vegetables in the monsoon without substantial costs. Beside these, many other social, economic, agricultural and ecological benefits are associated with the practice of floating gardening[1].

Despite long use in the southern floodplains, floating gardening was a completely new concept for the haor areas. The World Conservation Union (IUCN), Bangladesh Country Office therefore implemented a small-scale pilot project with CARE Bangladesh in 2005–2006 to introduce floating gardening and associated winter vegetable gardening in selected haor areas. The project was designed to contribute to the food security of targeted marginalized communities, and also to test the feasibility of floating gardening as an option for alternative livelihoods in vulnerable communities.

This paper documents the challenges faced in introducing this new agro-technique in the north-eastern wetlands of Bangladesh and the approaches taken to overcome challenges by increasing awareness and knowledge in the community. We also describe necessary adaptation of the technique specifically for the haor wetlands.

Project Area and the Target Community

Three villages (Adarshagram, Biddabhushan Para and Ghagrakona) of Baniachang 2 No. Uttar Paschim Union (longitude 91°22′ and latitude 24°33′) under Baniachang Upazilla of Habiganj District of Bangladesh were selected from the haor region of the north-east of Bangladesh. Out of a total of 388 households of the villages, 76% were identified as vulnerable, where selection criteria mainly included ownership of property such as land, a house, a boat, a fishing net, etc. A total of 21 vulnerable families (seven from each village) with 150 family members were selected for introduction and promotion of floating gardening and associated winter vegetable gardening.

The entire target population was landless, and almost all were illiterate. The population density (average 7 persons per family) and growth rate (average 5 children below the age of 15 per family) were very high[3]. The number of wage-earning members was between one and three per family. Wage-labor and fishing were the two most common jobs in the monsoon period (83%). In winter, the main jobs

were wage-labor in agricultural fields followed by carpentry and fishing. The household daily income ranged from US$0.8 to 4.0 with an average of about US$2.0 per day, both in the monsoon and winter. Therefore, the annual *per capita* income was calculated as US$104; very low compared with the national *per capita* income of Bangladesh (e.g. US$482 in 2005–2006[4]).

The society in general was conservative, and women were mostly engaged in housework. Potato (*Solanum tuberosum*) was considered as the staple vegetable, but leafy and fruit vegetables were obtained seasonally from local markets. Despite being wetland dwellers, people frequently had to buy fish from these markets. Although people knew that buying vegetables was much more expensive than growing them at home, homestead vegetable gardening was very limited.

Challenges

The pilot project focused on the livelihood and nutritional support of the marginalized populations. A number of challenges were identified at the beginning. These were:

1. Convincing the target community to take up floating gardening—an entirely new agricultural technique to them.
2. Assessing the availability of plant materials (e.g. water hyacinth) for construction of the floating platforms or, alternatively, identifying suitable materials to build the platforms.
3. Suggesting an appropriate floating platform size for the haor, keeping in mind the hydrology, social conditions and natural resources of the area.
4. Protecting the floating gardens from wave-action, using locally available materials.
5. Selecting appropriate crops and husbandry for maximum benefit from the initiative.
6. Promoting appropriate, low-cost techniques for balancing costs and benefits.

Methods

Rapid rural appraisal (RRA) was used for scoping floating gardening in haor. A questionnaire survey was carried out at the beginning of the project using a tested format mainly to establish the baseline of existing vegetable consumption and gardening in the monsoon and winter. Group and one-to-one discussions were conducted to encourage communication among the target communities about floating gardening, and training programs were organized. The project team monitored the activities of the floating gardeners at the field level on a regular basis. Fortnightly and per-visit reports by the project staff were useful in tracking the tangible and intangible changes taking place in the field. The impacts of the initiative were assessed at the end of the project with three separate questionnaires that collected input–output data and information on community dynamics, along with other issues.

Pre-project Vegetable Consumption and Gardening Scenario

A total of 30 different types of vegetable were consumed, cultivated and bought by the targeted families. Potato, eggplant (*Solanum melongena*), snake gourd (*Trichosanthes anguina*), ridged luffa (*Luffa acutangula*) and bottle gourd (*Lagerneria siceraria*) were the top five vegetables consumed by the villagers in the monsoon period, whereas potato, eggplant, tomato (*Lycopersicon esculentum*), hyacinth bean (*Lablab purpureus*) and amaranth (*Amaranthus tricolor*) were used in winter. Cauliflower (*Brassica oleracea* var. *botrytis*) and cabbage (*Brassica oleracea* var. *capitata*) were the other two major vegetables bought in the cold season. On average about US$0.30 was spent by each household per day to buy vegetables from the market.

Almost all surveyed households cultivated one or more vegetables in both seasons in the limited space in their homesteads and had been doing so on a limited scale, on average, for more than 10 years. The most common cultivated species in the monsoon were snake gourd, ridged luffa and amaranth, and in winter tomato, eggplant, hyacinth bean, potato and amaranth. Scarcity of land, lack of knowledge and infertile soil were identified as the main reasons for not undertaking extensive homestead vegetable gardening.

Most of the people grew vegetables only to meet their own needs, without any intention to sell but, when sold, most vegetables were bought by others living in their villages or by traders coming to the villages to buy their products. The respondents of the survey identified long distance of transportation, high transport costs and shortage of labor as the major constraints in marketing of vegetables.

Preparing the Communities

A number of measures were taken to prepare the communities for the project.

1. A total of 20 awareness meetings were organized at the project site to discuss floating gardening cultivation. Each meeting was attended by 10–25 villagers, of whom 70–100% were women.
2. The communities with enhanced awareness were organized into three Floating Garden Groups, each consisting of seven members (average male : female ratio = 3 : 4) who met regularly.
3. One formal training session on floating gardening and associated winter vegetable gardening was organized for all 21 participants. Topics included collection of platform-making materials, preparation of the floating garden and its protection from wave-action. Appropriate species for cultivation were suggested, and guidance was given for raising of seedlings and their transfer to the floating platforms, after-care, protection against birds and other pests and crop harvesting. A training manual was prepared in the national Bangla language,

Figure 2. A neighbor (in water) is helping a floating gardener to prepare a garden in Ghagrakona, Habiganj. (Photo: Haseeb Md Irfanuliah, IUCN Bangladesh.)

(Figure can be viewed in color in the Supplementary Materials for the online version of the paper)

and all Floating Garden Group members were provided with individual on-site training during preparation of their floating platforms in the monsoon of 2006.

4. To gain further experience, 20 participants visited the southern Bangladesh districts (Pirojpur, Madaripur and Gopalganj) where floating gardening has been traditionally practiced.

Floating Gardening in the Monsoon

Floating platform preparation

A total of 28 floating garden platforms were prepared in the monsoon of 2006, of which 25 were prepared by the Floating Garden Group members and three by non-target villagers who had been inspired by the activity of the project. Most of the families (*c.* 70%) prepared one platform; but two to four platforms were made by some members. The average length of the freshly prepared platforms was 4.6 m, width 1.4 m and height 1.1 m. The height decreased significantly to about 0.5 m after 2–3 weeks, when the platform had rotted and was ready to cultivate. The area of the platforms ranged from 3 to 33 m^2 with an average of 7 m^2. Generally, gathering of water hyacinth began 4.5 weeks before platform preparation.

The time taken to construct a platform varied from 0.5 to 6 person days (1 person day = 8 h), with a mean of 2.5 person days. In almost all cases, construction was intermittent, often being spread over a period of 7–10 days. While making the platforms, the gardeners were assisted by family members, relatives, neighbors or laborers (Fig. 2). Mostly (66% of cases), sons and husbands helped their parents and wives, respectively, in the construction.

The floating platforms were always sited near the gardener's house in shallow water (maximum depth 2 m).

Table 1. Vegetables and spices cultivated on floating gardens in the monsoon of 2006 in Habiganj.

English name	Scientific name
Ginger	*Zingiber officinale*
Cowpea	*Vigna sinensis*
Eggplant	*Solanum melongena*
Snake gourd	*Trichosanthes anguina*
Amaranth	*Amaranthus tricolor*
Ladies finger	*Abelmoschus esculentus*
Turmeric	*Curcuma longa*
Water spinach[1]	*Ipomoea aquatica*
Taro[1]	*Colocasia esculenta*
Mustard	*Brassica campestris*
Hyacinth bean	*Lablab purpureus*
Chinese amaranth	*Amaranthus tricolor*
Bottle gourd	*Lagerneria siceraria*
Pumpkin	*Cucurbita maxima*
Jute	*Corchorus capsularis*
Onion	*Allium cepa*
Ceylon spinach	*Basella alba*
Coriander	*Coriandrum sativum*

[1] Saplings collected from nature.

All sites were inundated during the monsoon and dried out in winter, when vegetables were cultivated in areas potentially suitable for winter gardening. In terms of the availability of water hyacinth, 21 floating platforms were prepared at sites where the plant was easily available, but in seven cases, people had to collect water hyacinth by manually operated country-boat from further away, taking about 20 min.

Vegetable cultivation

A total of 18 different kinds of vegetable or spice were cultivated on the floating platforms (Table 1). Bottle gourd, amaranth and pumpkin were the three most common species, being cultivated on more than 70% of the platforms. The seeds used were either bought from local markets (50%) or came from personal supplies, however, seeds of the top three cultivated vegetables were mostly (approx. 65%) bought from the market.

In the case of vegetables with large seeds, like bottle gourd, pumpkin and bean, one seed was first inserted in a small, semi-moist ball made of rotten water hyacinth. These balls were then placed in shade on the ground and kept moist. Once the seedlings were about 7 days old, the balls containing seedlings were transferred to the floating platform and placed about 30 cm apart. Small seeds, such as amaranth and jute, were spread directly on the platform. Taro and water spinach were collect from the wild and planted on the edge of the platform. On most floating gardens, one to five vegetable varieties were cultivated, but the maximum number was eight (Fig. 3).

Certain vegetables, e.g., amaranth were harvested 3 weeks after sowing. Taro and water spinach were harvested after a few weeks. Other vegetables required months before

Figure 3. A female floating gardener by her floating platform, Adarshagram, Habiganj. (Photo: Haseeb Md. Irfanullah, IUCN Bangladesh.)

(Figure can be viewed in color in the Supplementary Materials for the online version of the paper)

harvest of the first fruits. The monsoon of 2006 was not typical, and the water receded very quickly (see below). Hence, winter gardening methods became necessary even in October.

Protecting the floating platforms

Physical damage. A number of options were tested for protecting the platforms from physical damage due to wave-action or drifting. All were found suitable, depending upon the intensity of wave-action. Four common methods were:

1. Erecting bamboo sticks in the mud at regular intervals around the platform.
2. Inserting a bamboo pole in the middle of the platform. Sometimes rope or string was used to tie the pole to the bank.
3. Aligning the platform parallel with the bank, then restraining it on the open side with a floating banana trunk or thick bamboo pole, loosely tied to a tree on the bank.
4. Planting taro along the edge of the platform so that the dense taro root system bound and strengthened the platform.

Damage caused by biological agents. Birds (chickens and ducks), cows, rats, monitor lizards, insect pests and diseases can all cause damage to the crops grown on floating gardens. However, most of the participants did not consider it necessary to take any measures to protect their crops. Several farmers erected fences made of bush morning glory (*Ipomoea fistulosa*) stems around the platform edges, or used netting to protect the produce from bird-attack. Planting of taro densely around the edges also served the same purpose. When the water receded, cattle could reach the crops, necessitating the erection of fences. No measures were specific for protection from rats or monitor lizards, but fencing or netting could offer some protection against these species. The farmers were encouraged to use integrated pest management techniques. Ash was used by some farmers to protect seedlings and plants from pests, and only one member used chemical pesticides.

Winter Gardening with Floating Garden Residues

When the water receded, the farmers broke up the semi-moist floating platforms and mixed the residue with the soil for winter vegetable gardening. During the trials, seven plots were made by seven farmers using floating platform residues. The average area was 120 m^2 per plot. Common species of vegetables cultivated on the plots were tomato, spinach, potato, sweet potato and chillies. Harvests in February 2007 were good.

Input–output Analysis

Direct monetary investments in floating gardening were for seed purchase, hire of labor and boats, and the purchase of construction materials like bamboo and rope (Table 2). However, there were a number of additional indirect costs, such as for labor by the Floating Garden Group members and their families, and for bamboo or seeds taken from their own stocks. These costs should be considered when analyzing budgets. It should be noted that, in most cases, the family members worked on the floating or winter vegetable gardens in their spare time, and women engaged in platform-making had not been otherwise involved in income generating activities. Therefore, in almost all cases the farmers did not have to give up their regular jobs for floating gardening. Most of the floating gardens required low labor inputs (Table 2).

The monetary value of the vegetables or seedlings produced on the floating garden platforms was calculated. If indirect labor expenses were excluded, the average income (estimated from produce) over 5 months (floating gardening and winter gardening) was about three times that of the total expense.

Impacts of Floating Gardening in Haor

On social dynamics

One of the important successes of the floating gardening and associated winter gardening initiative was its positive impact on social dynamics. The communities of the project site as a whole were optimistic about the floating gardening initiative from its inception. Those who learned about floating gardening through the awareness and capacity building programs were enthusiastic in sharing the technique and the benefits with others. People's perception improved greatly over time. Neighbors helped each other in

Table 2. Input–output matrix for a single floating garden (surface area 7 m^2) and associated winter garden plot (120 m^2), 2006–2007. Cost as in February 2007 (US$1 = 70 Taka).

		Input (US$)		Output (US$)[1]	
No.	**Items**	**Range**	**Average**	**Range**	**Average**
	Floating gardening				
1.	Direct cost (hired labor, hired-boat, seeds and construction materials)	0.10–4.96	1.25		
2.	Indirect labor cost[2]	1.15–4.60	2.10		
	Winter gardening				
3.	Seed cost	0.60–4.30	2.40		
4.	Indirect labor cost[2] (estimated)		2.30		
	Total			*Total*	
	Including items 2&4	4.30–10.90	7.70	6.50–20.00	10.00
	Excluding items 2&4	0.90–4.50	3.30		

[1] Harvest over 150 days.
[2] Includes the cost of labor provided by the 'Floating Garden Group' members and their family members.

preparation of platforms when help from family members was not available. People also gave their garden produce to their relatives and neighbors, thus improving social linkages among families.

Community dynamics in terms of gender balance was also noteworthy. In the pilot study, about 60% of the Floating Garden Group members were women, and a good number of the family members, relatives or neighbors who helped in platform preparation were women. Gender balance was also ensured in the training and awareness programs, and for the visits to the southern floating gardens (40–50% women). In all the villages, husbands were very positive towards their wives' participation in the gardening and associated project activities. Moreover, when female members could not attend training events or visits for personal reasons, their spouses came forward to represent the families.

On nutritional security

The project increased food availability at the household level, as envisaged by the project. Most of the products (70%) were consumed by the families, with 14% given to relatives and neighbors and 16% sold to local buyers. Although not assessed, the increased vegetable consumption, in turn, is likely to have had a positive effect on the health of targeted households.

On livelihoods

In the first year, from a floating garden of 7 m^2 and a 120 m^2 winter garden plot, US$10 was added to household income during the 150 days of the project (Table 2). Floating gardening and associated winter gardening has therefore demonstrated its potential to be a good supplementary income option for haor, year round.

On land-holding capacity

Through floating gardening, people of the project area made productive use of the stagnant waters adjacent to their homes, which would otherwise remain unutilized in the rainy season. The floating platforms increased their land-holding capacity without significant cost. For the poor, marginal, landless people of the project site, enhanced land-ownership, although for a short period of time in monsoon only, meant a lot to them and created significant social impacts. Depending upon the size of the homestead, floating gardens with a total area of 20 m^2 can increase land ownership by 2–10% during the monsoon.

Limitations of Floating Gardening in Haor

Despite the encouraging impacts on livelihoods and food availability, a few constraints were encountered in some haor villages. The farmers were encouraged to share their problems, and most of them mentioned loss of seeds and seedlings owing to torrential rain. Collection of water hyacinth was an important problem for some farmers if there were not enough plants nearby, since they had to hire or borrow boats from neighbors in order to gather enough plant material. Other constraints cited were a lack of help to prepare the floating platforms, damage to the platforms by waves and problems with weeds. Just one or two respondents mentioned problems with hot weather, high labor costs, monitor lizards and collecting seed.

Furthermore, it was found that the time required for platform preparation ranged widely and was often longer than expected primarily because of variations in water hyacinth availability, the number of people involved and the size of the platform.

There was only one rainy season during the pilot project (2006) and it was unexpectedly rainless, causing a rapid decrease in water level in the haor. This caused difficulties for the farmers who made their platforms in July in shallow

waters next to their houses in the expectation of an increase of water depth to 1 or 2 m. In a few cases, the water receded by early September and, as a result, it was not possible to conduct reliable tests of the protective measures against wave-action.

At the beginning of the project it was envisaged that disputes might arise over land or water tenure issues, but as the pilot study was on a limited scale, with mostly one or two platforms per family, there was little scope for conflicts over land or water.

Only one–third of the gardeners made winter vegetable gardens using floating garden residues in 2006–2007. There were two main reasons: lack of sufficient land in and around the homestead and failure to take out a lease on land elsewhere, individually or collectively.

Comparison Between Floating Gardening in Southern Bangladesh and in Haor

The size of platform promoted in haor by the present initiative was much smaller than that traditionally practiced in the southern floodplains of Bangladesh, where platforms are 15–55 m long and 2 m wide. There were several reasons for using smaller platforms in the haor area, which is very different from the stagnant, calmer floodplains of the south, where water hyacinth is abundant.

- Shorter, thicker floating platforms were expected to be more resistant to wave-action and drifting.
- Narrower platforms were suggested so that they could be maintained from a boat or from the bank of the water body. This reduced the need for a farmer to stand on the platform, thus making it weaker and prone to wave-damage.
- Availability of water hyacinth was not equal in all the villages.

Nevertheless, those who made floating platforms in late July made larger platforms using bigger water hyacinths in relatively calm water.

Demand for seedlings is different in the two areas. In southern Bangladesh (e.g. Pirojpur District), there is large-scale seedling production and marketing, and returns are good and rapid but in the haor area, demand for seedlings is low.

Areas to Explore

The main target of this small-scale, pilot study was to meet household demands for vegetables, and thus the scope for marketing of produce was limited. Some gardeners, however, sold floating garden and winter garden produce, which comprised about one-sixth of total production up to February 2007. Large-scale vegetable seedling production, a profitable practice in southern Bangladesh, would not be feasible in the haor without detailed market assessment. On the other hand, there is good scope for selling vegetables in the local markets, as well as in nearby niche markets in the towns. Vegetables like amaranth during the monsoon, and potato, sweet potato and tomato in winter could easily be sold in the local markets. In the study, most of the bottle gourd and pumpkin seedlings raised on the floating platforms did not survive because of the unusual monsoon, but the potential should be explored for cultivation of these varieties as winter vegetables, along with cabbage and cauliflower.

Floating gardening is not suitable for all the haor villages in Bangladesh, but it could be promoted in those haor areas where water hyacinth is easily available on the sheltered sides of the villages. Stagnant, polluted water with water hyacinth should, however, be avoided because of the potential risk of infectious diseases.

The visits to working floating garden systems in the south of the country were found to be very effective in teaching this novel technique, and could be included in any similar pilot study or future extension of the idea.

The involvement of existing community-based organizations (CBOs) could be explored in relation to the longevity of similar pilot initiatives. In the present project, CBOs of the SHOUHARDO (Strengthening Household Ability to Respond to Development Opportunities) Program of CARE Bangladesh were considered. A good relationship with the local government office (Union Parishad Office) was found to be very useful in introducing the novel agricultural technique to local marginalized people.

The project has indicated considerable potential to introduce floating gardening to other haor areas of Bangladesh, and promises to continue improving the food security and livelihoods of people living in haors.

Floating Gardening for Aquatic Weed Management

In many countries of the world, water hyacinth is a major invasive alien species causing serious problems in the water systems[5]. Over the past two decades or so, severe environmental, social and economic impacts of water hyacinth infestation have been estimated for many Asian and African countries[6–11]. The management of water hyacinth has included mechanical, chemical and biological measures. Of these, biological control using weevils and moths has been practiced successfully in many African countries as an environment-friendly measure[8,12–14]. Biological control, however, might not always be successful in controlling water hyacinth[11,15], and the risk of resurgence is always on the horizon.

In addition to environmental concerns from their use, physical and chemical control methods are expensive and have to be repeated every year, hence developing countries often cannot afford to support such measures[16,17]. Another way to potentially control invasive aquatic plants like water hyacinth, water lettuce (*Pistia stratiotes*) and salvinia (*Salvinia molesta*) could be utilization of the weeds for

financial gain[17,18]. This could involve energy production[19], use in agriculture as biofertilizer, or as a nutritious growing medium for mushrooms[18–20], however, this type of use in local communities has been uncommon[18]. As shown in Bangladesh, participatory approaches through CBOs such as the Village Development Committee could be a good option for management of natural resources, including aquatic weeds[1,21,22].

Floating gardening using aquatic weeds could be a useful method of managing aquatic weeds while improving the local food supply and economy, and improving the environment as a whole. It holds particular promise for the African large water bodies (e.g. Lake Victoria[10]) where water hyacinth is a serious nuisance, and could contribute to a better nutritional balance for people whose diet often depends on just fish. Floating gardening is a simple means of vegetable gardening on water, however, pilot studies are essential in order to develop country- and ecosystem-specific gardening systems that include evaluation of platform-making materials, measures for protection of platforms and crops against physical and biological stresses, the marketing of produce and overall sustainability of the initiative.

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Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations

Julia Olmstead[1,*] and E. Charles Brummer[2,†]

[1]Graduate Program in Sustainable Agriculture, Department of Agronomy, Iowa State University, Ames, IA 50011, USA.
[2]Center for Applied Genetic Technologies, Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602, USA.
*Corresponding author: jeo@iastate.edu

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Abstract

The transition away from forage-based cropping systems in Iowa to corn and soybean rotations since World War II has corresponded with degraded economic and environmental conditions in the state. Falling net incomes for farmers and concern over global warming and the effects of agriculture-related pollution on water, wildlife and human health have increased interest in diversified cropping systems. This paper reviews the benefits of diversifying Iowa corn and soybean rotations with perennial forage species such as alfalfa and red clover. Perennial forage crops improve soil quality, decrease NO_3-N leaching and soil erosion, increase carbon sequestration and decrease pesticide and herbicide needs by controlling weed and insect pests. Forage legumes reduce N fertilizer needs for succeeding corn crops at a higher rate than soybeans, and corn crops following forages have higher yields than after corn or soybeans. Farmers who add alfalfa to corn and soybean rotations could realize significant economic gains. A simulated 5-year rotation in Iowa including corn–soybeans–oats/alfalfa–alfalfa–alfalfa would result in a 24% net income increase over 5 years of corn–soybean–corn–soybean–corn, even with government farm support payments for the row crops. Farm policies that encourage commodity production create little incentive for Iowa farmers to diversify their cropping systems beyond corn and soybeans, despite the clear economic and ecological benefits. We recommend increasing federal support for conservation programs that reward environmentally beneficial farm practices such as the Conservation Securities Program and we encourage land grant universities to hire researchers interested in alternative agricultural systems.

Key words: forages, alfalfa, corn, cropping systems, alternative agriculture, farm policy

Introduction

Prior to World War II, forage species, used for pasture, silage and hay, were routinely included in Iowa crop rotations. By providing feed for livestock and work animals, cash income to farmers from hay sales and crucial ecological benefits to the farming system, these multi-functional crops mitigated risk on the farm. The post-war influx of cheap, abundant chemical fertilizers and synthetic pesticides, along with a shift from animal to machine-based labor, caused a decrease in forage-based cropping sequences[1,2], in part because farmers did not need to rely solely on forage legumes to supply nitrogen nor did they need feed for draft animals.

Since 1950, Iowa agriculture has increasingly focused on intensive corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production, an effort that produced impressive results—corn and soybean yields nearly quadrupled and more than doubled, respectively, between 1950 and 2004[3]. Ironically, these yield increases did not represent improved welfare for Iowa farms or farmers. During the same period of time, the number of farms in Iowa decreased by more than 50% and crop prices plummeted[4]. After adjusting for inflation, average net income per Iowa farm in 2001 was 9% lower than it was in 1960, despite a more than twofold increase in the number of acres per farm[4].

Meanwhile, the environmental implications of intensive corn and soybean production are cause for concern. Runoff and artificial drainage from corn and soybean fields are

†brummer@uga.edu

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well-documented causes of non-point source contamination of surface and groundwater bodies with sediment, nutrients (especially NO_3-N and P)[5–8], and pesticides[9–13]. NO_3-N loading to the Mississippi River from agricultural operations in the Mississippi River Basin has been linked to a hypoxic zone in the Gulf of Mexico that is growing in size and severity[14]. Further, pesticide and herbicide use in corn and soybean production may have negative effects on human and wildlife health[15–17].

We hypothesize that diversifying Iowa corn and soybean rotations by including forage crops would offer farmers a way to mitigate negative environmental impacts caused by corn and soybean production while providing a lucrative source of income not dependent on government subsidization. In this paper, we review the literature on the agronomic and ecological effects of forage incorporation into Iowa and Midwestern cropping systems. We also look at the economic effect of incorporating forages into corn and soybean rotations in Iowa and assess socio-political barriers that discourage farmers from including forage species as part of their agricultural systems. Finally, we make recommendations for policy changes that would encourage the adoption of forages by corn and soybean farmers, a goal that has the potential to greatly improve not only the ecological health of Iowa waterways and soil but also the economic health of the state's farmers. Although this analysis primarily focuses on Iowa, the discussion and conclusions can likely be generalized to other agroecosystems as well.

Forage Production

Forage is defined as the edible part of a plant, other than the separated grain, that is generally above ground and that can provide feed for grazing animals or can be harvested for feeding[18]. In Iowa, several grass and legume species are cultivated as forages, including smooth bromegrass (*Bromus inermis* Leyss.), orchardgrass (*Dactylis glomerata* L.), switchgrass (*Panicum virgatum* L.), red (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.), birdsfoot trefoil (*Lotus corniculatus* L.), and most commonly, alfalfa (*Medicago sativa* L.)[19]. Forages can be harvested by animals in pasture-based systems or mechanically harvested throughout the growing season as silage/haylage, hay or pellets for use as year-round livestock feed.

Precise estimates of the amount of perennial forage crops grown in Iowa are not available. Iowa has between 1 and 2 million ha of pastureland, encompassing cropland, permanent and woodland pastures[19]. An additional 650,000 ha of hay were harvested in Iowa in 2004, 525,000 ha (81%) of which was alfalfa[20]. This represents 7% of Iowa's crop harvest, which also includes corn, soybeans, oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.).

Relative to corn and soybeans, perennial forage crops have high caloric and protein yields, and high output/input energy ratios. Based on energy data from production in Ohio, alfalfa yields nearly twice as many calories and protein per hectare as soybeans and more than 40% more protein than corn per hectare. The energy output/input (energy inputs include labor, machinery, fuel, fertilizers, pesticides, electricity and transportation) ratios for alfalfa, soybeans and corn are 6.17 : 1, 4.15 : 1 and 2.5 : 1, respectively[21]. The relative energy efficiency of alfalfa over a corn and soybean rotation is mainly the result of the high energy cost of nitrogen fertilizer applied primarily to corn.

Agronomics

Rotational yield benefits

Little debate exists over the yield benefits arising from diversifying crop rotations, particularly those combining legume and grass crops in succession. A rotation of corn and soybeans yielded 10% more than continuous corn and 8% more than continuous soybeans in Minnesota, evidence for a 'rotation effect'[22]. Adding perennial forage legumes, particularly alfalfa, to the system creates more substantial benefits to corn yield, a trend that has been observed for over 50 years and in many regions of North America[23–33] (Table 1). In Minnesota, a single year of alfalfa increased succeeding corn yields by 19%[24] to 84%[22] compared to corn following corn and by 33% compared to corn following soybeans[22]. Even when nitrogen is applied to the corn crop, corn following alfalfa typically yields more than corn following soybeans[34]. These studies demonstrate that rotations including at least 1 year of alfalfa would produce higher corn and soybean yields than the typical corn–soybean rotation. Because the preceding alfalfa crop supplies nitrogen to the corn for free, the higher yield is produced at lower input cost as well. Yield benefits conferred by alfalfa occur in sub-humid regions like the Midwest or in areas under irrigation. When water availability is restricted, alfalfa, which uses large quantities of water, can decrease subsequent corn yields[35].

Weed effects

In recent years, Iowa farmers have sprayed more than 95% of corn and soybean fields annually with herbicides[36]. Evidence of human and animal toxicity of the most frequently applied herbicides—atrazine for corn and glyphosate for soybeans—has raised concerns about their widespread use[15–17]. In particular, the widespread adoption of Roundup Ready® soybeans and corn has resulted in a large increase in the application of Roundup® (glyphosate), which is now present in many water samples in the Midwest[37]. Further, herbicide-tolerant crops do not solve the weed control problem; resistance has developed in many weed species to herbicides like Roundup®, diminishing the value of the technology[38]. In other words, the technological fix of herbicide-resistant crops is transient, requiring continual reinvigoration by more advanced technology.

Table 1. Corn yield following corn, soybeans or alfalfa across ten environments.

Preceding crop						
Corn	Soybeans	Alfalfa	Alfalfa–corn as % of corn–corn	Location	Year	Reference
---kg ha^{-1}---						
267	–	748	280%	IA	1948	31
1599	–	4792	300%	GA	1970	32
1670	–	5170	310%	ON	1976	25
3700	5100	6800	184%	MN	1986	27
852	–	1642	193%	PA	1988	29[1]
8709	9126	9031	104%	MN	1994	33[2]
7860	8130	9270	118%	MN	1997	23
5084	7015	7966	157%	ON	2003	30
3830	6140	7300	191%	SD	2005	24
7407	7407	9416	127%	MN	2005	26

[1] The corn yield values come from Table 1, with the comparison being corn following corn with no nitrogen application versus corn following alfalfa in 1984.
[2] Comparisons from Table 2 and crop yields in 1994, which is the only year with corn grown directly after all three crops.

In contrast, alfalfa and other forages planted in rotation with corn and soybeans offer non-chemical means of controlling weeds. When grown in monoculture, alfalfa stands decrease or eliminate populations of several weed species, including milkthistle [*Silybum marianum* (L.) Gaertn.], field bindweed (*Convulvulus arvensis* L.), white campion [*Silene latifolia* subsp. *alba* (Mill.) Greuter & Burdet; syn. *Silene alba* (Mill.) E.H.L. Krause], and common lambsquarter (*Chenopodium album* L.)[39–42]. By their second year, alfalfa stands can often be weed-free without any herbicide use[43,44]. Without decreasing yields of succeeding crops, alfalfa has been shown to reduce weed densities to a comparable degree as herbicides[45–47]. A recent demonstration of one alternative system has shown that diversifying crop rotations to include triticale and either red clover or alfalfa is nearly as effective as herbicide use in controlling velvetleaf (*Abutilon theophrasti* Medik.) and foxtail (*Setaria faberi* Hermm.), two of the most prevalent weed species found in corn and soybean crops in the Midwestern US[48].

Soil nutrients

All plants require nitrogen for growth. Corn, like most grass species, cannot fix its own nitrogen and must mainly rely either on synthetic fertilizer or animal manure nitrogen inputs or on nitrogen that has been fixed by a legume species planted before it. Soybeans are legumes, and hence fix nitrogen, but in quantities insufficient to fully meet the N demands of themselves or of successive corn crops. In contrast, alfalfa can fix up to nine times more N than soybeans, birdsfoot trefoil up to four times as much, and red clover up to five times more[49]. Sweetclover (*Melilotus* spp.), once widely planted throughout the Midwest and Great Plains, can produce even more N than these species[50]. The value of alfalfa for increasing soil nutrient levels has been documented since at least the time of the Roman agronomist Columella, who wrote sometime around 100 CE that alfalfa 'dungs the land'[51]. The decomposing alfalfa crop results in more mineralizable N than either soybean or corn crops[52], further demonstrating the value of the crop in providing nitrogen for crop production.

Alfalfa's superior nitrogen fixation rate enables it to reduce the economically optimum N fertilizer rate needed for corn production by a greater magnitude than soybeans. Iowa State University recommends a reduction in the application rates of N fertilizer to corn following alfalfa by 80–85% compared to 0–25% for corn following soybeans[53]. Alfalfa in rotation with corn contributes an 18–50 kg ha^{-1} larger nitrogen credit than soybeans, depending on the condition of the stand when rotated out of alfalfa[54]. In addition to cost savings for nitrogen fertilizer, this credit also results in a considerable reduction in the amount of nitrogen leaving the agroecosystem[33,55,56].

Soil quality

Forage legumes and grasses improve soil quality as determined by multiple indicators, including improved soil organic matter (SOM) and physical properties[26,57–66] (Table 2). Additionally, 5 years of continuous alfalfa increased the mean weight diameter of water-stable aggregates (an indicator of soil quality) from 1.5 to 2.3 mm and C content increased from 26 to 30 g/kg[67]. In comparison, 5 years of corn and fallow resulted in neither an increase nor decrease in soil quality[68]. Alfalfa, bromegrass and red clover increased soil structural quality, as indicated by a decrease in dispersible clay and an increase in wet aggregate stability, compared to continuous corn grown under either conventional or no-till conditions, which showed either no improvement or some decline in soil structural quality[57].

Table 2. Soil quality and ecological benefits contributed by forages.

Ecological indicator	Data	Reference
SOM	148% greater SOM with C-S-O/A-A-A than C-S-C-S-C	26
Soil organic C (SOC)	24% greater SOC in C-C-O-A than C-S	66
Subsurface drainage	54% less subsurface drainage in A-C-C than C-S	33
Nitrogen loss	14% less NO_3-N loss in A-A-A-C-O-S than C-S	55
Nitrogen loss	37% less NO_3-N loss in A-C-C than C-S	56
Nitrogen loss	23–77% lower N loss in A-C-C than C-S	33
Wildlife habitat	Eighteen times more wildlife in A than in a field by chance	67

C, corn; S, soybeans; O, oats; A, alfalfa.

Ecological benefits

Recent decades have seen growing concern over the widespread damage caused by row cropping, including soil erosion, nutrient contamination of waterways and contribution to excess greenhouse gas emissions[33,69,70]. Cropping systems that reduce or mitigate these problems are essential if agricultural systems are to be environmentally sustainable in the long term. Crop rotations that include forages can help reduce negative impacts of agriculture on the environment, as compared to rotations that only include corn and soybeans, through decreased NO_3-N leaching and water drain flows[33,55,56,71] and by increased C sequestration[59,66,68,72–77] (Table 2). Additionally, forage crops can also play an important role in providing critical wildlife habitat for many species of migratory birds and small mammals[51,67] (Table 2).

Economics

Few formal economic comparisons exist that calculate production costs and profits on Midwestern farms with corn and soybean rotations as compared to those with alternative rotations including forage crops such as alfalfa[65,78–81]. Case study economic analyses, however, often show alternative rotation schemes to be economically competitive with, or frequently advantageous over, rotations of only corn and soybeans[65,78,79,81,82]. Additionally, a number of analyses show that forage-based livestock production systems are economically advantageous over grain-based livestock systems or row-crop systems[83,84].

To illustrate the economic differences between a corn–soybean rotation and two alternative rotations in Iowa, we compared estimated production costs and incomes on an average-sized Iowa farm. This analysis does not pretend to be exhaustive or to take into consideration the complexity of factors influencing production costs and income on Iowa farms. Variables such as yield differences between farms, the effects of precipitation and pest stress, management differences, or the complexity and variation of incomes from government payments will affect any given farmer's bottom line. This analysis seeks solely to compare production costs and farm incomes based on average farm size, management practices, input costs, prices and government payments.

According to 2005 statistics from the Iowa Department of Agriculture[20], average farm size in Iowa is 143 ha, so we set our generalized farm size equal to that figure. This analysis could be scaled up or down for other farm sizes and the income differences between the systems would change proportionally. According to 2002 statistics on land tenure rates, Iowa farmers on average rent 59% of the land they farm, so on our generalized farm we assumed 81 ha were rented and 62 ha were owned[85]. The cropping systems analyzed were as follows:

Conventional: corn–soybean
Alternative 1: corn–soybean–oat/alfalfa
Alternative 2: corn–soybean–oat/alfalfa–alfalfa–alfalfa

The *conventional* system, an annual corn and soybean rotation, represents the most common cropping system found in Iowa. For our purposes, we assumed that 1/2 of the farm was planted to each crop each year. *Alternative 1* includes an oats/alfalfa mix. Thus, in any given year, 1/3 of the farm is in corn, 1/3 in soybean and 1/3 in oat/alfalfa; crops would be rotated year-to-year in that order on each of the thirds. Oats would be harvested for grain and the straw baled; a single alfalfa harvest would be taken one month after oat harvest. Alfalfa regrowth would be plowed down, adding value as an N fertilizer to the succeeding corn crop, but not considered in our economic analysis. For the *Alternative 2* rotation, the farm is divided into five fields, with one in corn, one in soybeans, one in oats and establishing alfalfa and two in established alfalfa in any given year. During the two post-establishment years of alfalfa production, four harvests are made each season.

Crop production costs were obtained from Iowa State University Extension estimates, which include fixed and variable expenses such as machinery and fuel, seeds, chemical inputs (including pesticides and fertilizers), labor and land[86]. Actual crop prices were obtained from the Iowa Department of Agriculture[20] (except for the average price of oat straw, which was obtained from the *Hay and Forage Grower* Web site[87]) (Table 3). Government payments, including direct and counter-cyclical payments (DP and CCP), were estimated as described below using formulas and figures provided by the Farm Services Agency of the United States Department of Agriculture (USDA)[88]. DP

Table 3. Assumed crop yields (kg ha^{-1}) and average crop prices (US$ Mg^{-1}) for the years 2001 through 2005.

	Assumed yield[1]					Average price[2]				
Crop	**2001**	**2002**	**2003**	**2004**	**2005**	**2001**	**2002**	**2003**	**2004**	**2005**
Corn	8467	8467	9408	9408	9408	$75	$87	$93	$75	$73
Soybeans	3024	3024	3024	3024	3024	$160	$204	$105	$186	$197
Oats	2867	2867	2867	2867	2867	$106	$123	$106	$103	$117
Oat straw	907	907	907	907	907	$66	$66	$66	$66	$66
Alfalfa (established)	5442	5442	5442	5442	5442	$100	$94	$90	$95	$89
Alfalfa (first-year)	907	907	907	907	907	$100	$94	$90	$95	$89

[1] kg ha^{-1} for corn, soybeans, and oats, and kg ha^{-1} cutting^{-1} for oat straw and alfalfa.
[2] US$ Mg^{-1}.

Table 4. Simulated production costs, gross returns and net returns for three cropping systems on an 'average' 143 ha Iowa farm for the years 2001 through 2005.

		Cropping system		
Year		**Conventional[1]**	**Alternative 1[2]**	**Alternative 2[3]**
2001	Cost	$91,568	$84,314	$93,670
	Gross return	$79,822	$85,479	$128,383
	Net return	−$11,745	$1165	$34,712
2002	Cost	$90,896	$83,214	$90,922
	Gross return	$96,899	$98,416	$131,062
	Net return	$6003	$15,202	$40,140
2003	Cost	$94,786	$86,823	$95,659
	Gross return	$117,628	$109,624	$135,245
	Net return	$22,842	$22,802	$39,586
2004	Cost	$100,013	$91,887	$100,099
	Gross return	$90,412	$91,421	$127,288
	Net return	−$9601	−$465	$27,189
2005	Cost	$105,799	$97,435	$109,177
	Gross return	$91,471	$93,516	$124,309
	Net return	−$14,328	−$3919	$15,132

[1] C-S.
[2] C-S-O/A.
[3] C-S-O/A-A-A.
C, corn; S, soybeans; O, oats; A, alfalfa.

were estimated with the formula, DP = DP rate × base acreage × 85% × DP yield, where the DP rate was set in the US Farm Bill, the base acreage is based on the historical acreage in crop production (assumed to be the entire program crop area on our generalized farm), and the DP yields are equivalent to those listed in Table 3. CCP were estimated using the formula, CCP = Target price − Market price × Base acreage × 85% × CCP yield, where the target price was set in the US Farm Bill, market prices are given in Table 3, and CCP yields are equivalent to those listed in Table 3.

Yields used in the analysis for corn, soybeans, alfalfa, oats and oat straw were the average yields used to determine production costs in the Iowa State University Extension publication[86] (Table 3). These yields were used for all of the systems, despite the fact that yields may differ depending on the rotation employed, as we described in earlier sections of this paper. Similarly, the various ecological benefits of a system including forage crops are not accounted in this analysis.

To make our estimates, we obtained average crop production costs and returns in each year for each system (Table 4) and calculated average net income across five years (the length of the longest rotation) from each production system. Government payments were also averaged across years. Net returns are equal to gross income (including deficiency payments when government programs apply) minus all production costs. Average net returns for the entire 5-year rotation were calculated with and without government program payments for each system (Table 5).

Profitability of the cropping systems was based on production costs, prices obtained by farmers for crops, and in some cases government program payments. Our

Table 5. Whole farm gross and net returns with and without government program payments for three cropping systems on an 'average' 143 ha Iowa farm from the years 2001 through 2005.

	With government payments		Without government payments	
Cropping system[1]	5-Year gross returns (rank)[2]	5-Year net returns (rank)	5-Year gross returns (rank)	5-Year net returns (rank)
Conventional	$543,474 (3)	$60,413 (3)	$476,232 (3)	−$6829 (3)
Alternative 1	$525,524 (2)	$81,852 (2)	$478,456 (2)	$34,784 (2)
Alternative 2	$674,527 (1)	$185,000 (1)	$646,287 (1)	$156,760 (1)

[1] Conventional = C-S, Alternative 1 = C-S-O/A, Alternative 2 = C-S-O/A-A-A; C, corn; S, soybeans; O, oats; A, alfalfa.
[2] The rank of 1 is highest value.

calculations clearly show that the Alternative 2 rotation, with 3 years of alfalfa, is the most profitable, whether government payments are included or not. Alternative 1, with only 1 year of alfalfa, ranks second in profitability, both with and without government payments. The conventional system, which does not include forage, is the least profitable system, and results in a net loss without government payments.

Despite the increased costs associated with alfalfa production (which include factors such as additional machinery and labor), the price obtained for the crop makes the system with 3 years of alfalfa very profitable, 43% more than the conventional system even when including government program payments. According to our analysis, adding only 1 year of alfalfa to a corn–soybean rotation (Alternative 1) decreases profitability of the system compared to Alternative 2, due to the relatively high cost of alfalfa seed, costs associated with planting and low yield of alfalfa in the establishment year.

The most profitable cropping system in our analysis contained 3 years of alfalfa. Prices of alfalfa vary with production levels in local markets and are not eligible for government deficiency payments. An increase in alfalfa production due to inclusion of the crop on more Iowa farms could therefore lead to depressed alfalfa prices. Future studies will need to consider the lowest prices for alfalfa at which the producer would have a net income equivalent to conventional systems, both with and without government program payments. A price sensitivity analysis could also indicate the economic feasibility of increased production levels and the need to consider new markets (other than hay) for alfalfa and other forages as production increases. One possibility could be the expansion of pasture-based livestock systems, demanded by a growing consumer sector[89] and offering many ecological services as compared to decoupled row crop and livestock systems[90]. The bottom line from our analysis showed that even without accounting the many positive externalities generated by alfalfa (or forages in general), profitability of the cropping enterprise increased with the inclusion of a forage component during the years 2001–2005.

Table 6. Whole farm gross and net returns with and without government program payments for corn versus alfalfa on an 'average' 143 ha Iowa farm in 2006.

	With government payments		Without government payments	
Crop	2006 Gross return	2006 Net return	2006 Gross return	2006 Net return
Corn	$204,525	$70,600	$172,352	$38,428
Alfalfa	$180,030	$53,209	$180,030	$53,209

The rapid expansion of the ethanol industry has caused a recent spike in corn prices that this economic analysis does not account for. Corn prices rose to four dollars per bushel at the end of 2006 and in early 2007[3]. Farmers have responded by increasing planned corn acreage in Iowa for 2007[91]. Although alfalfa (and most other crop) prices have risen along with corn, the high corn prices of 2006 made corn, on average, more profitable than alfalfa. To examine the change to farm income from the corn price increases, we compared net income from corn versus alfalfa, with and without government payments, on our sample farm, using 2006 average prices and government pay rates, 2006 production costs, and the same size and rented versus owned land proportion assumptions as in our original analysis[85,86,88]. With government payments included in net income estimates, 1 year of corn in 2006 was 25% more profitable than alfalfa. When government payments were excluded, however, alfalfa was 38% more profitable than corn in 2006 (Table 6).

Barriers to Forage Incorporation

Our review of the literature and a simple cost–benefit analysis using average input costs and output crop value demonstrate numerous agronomic, ecological and economic benefits that are being attained on Iowa farms that include forages in rotation with corn and soybeans. Why don't more farmers grow forage crops? We surmise that the combination of government policies, market dynamics,

time constraints from off-farm employment, and culture has influenced the hesitancy of many farmers to diversify cropping systems.

Perhaps most importantly, US agricultural policies subsidize a narrow set of commodities in Iowa including corn, soybeans and, to a limited extent, oats. USDA subsidies for Iowa farms totaled $12.5 billion between 1995 and 2004, with corn and soybean production receiving 83% of those dollars, while only 15% went toward conservation programs (mainly the Conservation Reserve Program)[92]. These policies are really a means of risk management, guaranteeing farmers a return on commodity crops regardless of the many uncontrollable variables that may impinge on production. Without similar risk avoidance for other crops, farmers would naturally be loath to grow them. Further, the programs essentially reward maximization of commodity production, offering little incentive for diversification of crop rotations or incorporation of perennial crops into agricultural landscapes.

Without policy incentives to encourage cropping system diversity (or at a minimum, policies that do not encourage corn and soybean production), many Iowa farmers are unlikely to take steps to incorporate forages into their cropping systems. A survey of row crop farmers in central Iowa found that 40% of respondents would be 'not willing at all' to convert to a cropping system incorporating more forages. However, another 40% said they would be 'somewhat willing', and 20% of respondents said they would be 'very willing' to add forages. Of those who were not willing at all, reasons cited included preference for their corn–soybean rotation, the need for increased labor, and the need for new equipment. Survey respondents also cited a lack of market incentives as the most serious obstacle to adoption of more ecologically sound farming practices[93].

Until recently, the relatively low cost of synthetic nitrogen fertilizers and fuel has meant that farmers often did not view energy costs alone as a significant incentive to make changes in agricultural systems. Recent increases in non-renewable energy costs, however, may mean farmers will consider alternative crop production systems that require fewer energy inputs, such as forage-based rotations[94].

Conversely, rising energy costs may increase demands for biofuels such as corn-based ethanol and soy biodiesel. Although comprehensive economic analyses for this scenario have not yet been done, projections from the USDA and World Resources Institute show a substantial increase in corn production over the next decade to meet biofuel demands[94,95]. Recent corn price increases fueled by ethanol demand means corn has lately become as profitable as or more profitable than alfalfa (Table 6). Corn acreage will expand in the near future, a scenario that will come with very high environmental costs. On the bright side, with the advent of ethanol from cellulose, many forage crops could be dual use—livestock feed or biofuel feedstock—and thus, could contribute in a sustainable way to a bioenergy future.

Recommendations for Change

Forages offer potential ecological, economic and agronomic benefits to midwestern agricultural landscapes and producers, and many farmers already incorporate forages into their systems. We see three possible avenues toward increasing the role of forage crops in the Midwest and throughout the country: revamped farm policies that stress conservation rather than production, a reinvigorated agricultural research paradigm that recognizes that the public interest is not always served by industry, and a more vocal forage research sector.

Without government policies that encourage alternative agricultural systems, farmers are unlikely to make changes to their crop rotations. Future farm policy should encourage diversification of agricultural landscapes and should reward environmental services provided by farmers. US farm policies should support forage production for hay and pastures, which would increase the numbers of ruminant livestock on the land. Increased pasture-based livestock production could lead to higher net incomes for farmers while simultaneously decreasing N fertilizer use and soil erosion, thereby improving water quality and increasing carbon sequestration[83,96].

We recommend increased funding and support for two programs within US farm policy intended to promote agricultural biodiversity and conservation: the Sustainable Agriculture Research and Extension Program (SARE) and the Conservation Security Program (CSP). SARE is a competitive grant program for research and outreach that funds farmer-, citizen- and researcher-driven projects, and has been shown to be effective at increasing sustainable production practices[97]. The promotion of researcher–farmer collaboration with a goal of increased diversity and sustainability on agricultural landscapes that is supported by SARE is crucial both to encourage positive changes on farms and to influence research priorities within land grant universities.

The CSP offers payments to farmers and landowners for carrying out conservation practices on working agricultural land. Unlike the Conservation Reserve Program (CRP), where the government essentially rents marginal land to establish grasses or wetlands, the CSP seeks to reward farmers whose agricultural practices provide ecological services such as soil erosion reduction and increased biodiversity. While the CRP has resulted in decreased erosion and increased biodiversity on some marginal lands, its costs have included a reduction in the number of working farms as well as reduced rural community vitality[98]. We recommend increased funding and expansion of incentive programs like the CSP that, rather than encourage increased commodity production, promote farming practices that provide both livable incomes for farmers and ecological benefits.

Secondly, because forage-related research currently attracts little funding from the agribusiness industry and is unlikely to receive substantial industry support in the

future, agricultural research at the state land-grant institutions and through the USDA Agricultural Research Service (ARS) needs to include a critical mass of forage scientists. Data for public sector forage breeding show that the number of breeders has declined by 26% across all forages and by 46% for alfalfa just in the period from 1994 to 2001[99]. Therefore, encouraging universities and the USDA-ARS to hire scientists willing to investigate the full range of alternative production systems would enable forage crops to gain a higher profile. Land grant universities need to develop alternatives that help farmers remain on the land while being economically stable and environmentally sensitive, rather than simply following the lead of industrialized agriculture. Funding for agricultural research from state legislatures is declining and research support is increasingly based on extramural funds through governmental agencies like USDA or NSF. These programs need to be crafted to enable the long-term nature of perennial forage crop research to compete successfully.

Finally, forage scientists need to do a better job of relaying the importance of their research to funding agencies, the government and to the public. Although we often complain about the limitations constraining our field, we do not often take the initiative to write letters to the editor or to our congressional delegations supporting our field and on the importance of forages to esthetically pleasing, environmentally beneficial and economically sustainable farming systems.

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Effects of soil fungi on weed communities in a corn–soybean rotation

N. Jordan* and S. Huerd

University of Minnesota, 411 Borlaug Hall, 1991 Upper Buford Circle, St Paul, MN 55108, USA.
*Corresponding author: jorda020@tc.umn.edu

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Abstract

In a variety of ecosystems, interactions between soil microbiota and weedy plants can strongly affect population and community dynamics of these plants. However, weed–soil microbe interactions are not well characterized in field-crop agroecosystems. In Minnesota (USA), we repeatedly applied a fungicide (benomyl) to field plots in a corn–soybean crop rotation in each of 3 years, and sowed experimental weed communities containing host species for arbuscular-mycorrhizal fungi (AMF) and non-host species. Benomyl typically suppresses formation of mycorrhizal symbiosis in AMF-host plant species, and may also affect other soil fungi. We assessed weed density and biomass production, and monitored AMF colonization rates in each of 3 years. We found that weed density, biomass, community composition and the relative performance of AMF-host and non-host weed species were all significantly responsive to fungicide applications, although for all attributes responsiveness was variable. Fungicide application increased total weed density and biomass production in nearly all cases; most effects were modest but reached a maximum of 49%. Fungicide application also increased the relative performance of non-host species in most cases, although most effects were again modest. Our findings are the first assessment of responses by field-crop weeds to direct manipulation of soil microbial communities in a field setting, and suggest that the population and community ecology of these weeds can be strongly affected by the fungal component of soil microbiota.

Key words: weed ecology, soil microbiology, plant–soil interaction, mycorrhizae, weed biocontrol

Introduction

Recently, it has become evident that interactions between invasive plants and soil microbes can facilitate plant invasions of nature reserves and range-land agroecosystems, support the persistence of these invasions, and reduce prospects for restoration of more desirable plant communities[1–3]. However, relatively little is known about interactions between field-crop weeds and soil microbes[4]. Current trends in management of field-crop agroecosystems are promoting practices that tend to stabilize the soil environment, which will likely increase the importance of weed–soil microbe interactions. These practices include cover cropping and conservation tillage. Cover crops have been shown to increase diversity and abundance of arbuscular-mycorrhizal fungi (AMF)[5], affect soil-borne pathogens[6,7] and increase microbial antagonists to soil-borne pathogens[8]. Conservation tillage methods reduce physical disturbance of the within-soil hyphal network formed by AMF[5,9,10] and thereby promote plant interactions with AMF. If current trends in field-crop agroecosystems are intensifying plant–soil microbe interactions in these systems, what might be the effects on field-crop weeds?

Previous work on weed–soil microbe interactions in field-crop agroecosystems has emphasized weed interactions with microbial antagonists, chiefly deleterious root-associated bacteria[11–13], AMF[14] and bacterial and fungal predators of weed seeds[15]. These investigations have suggested that 'weed-suppressive' soils might be developed; such a soil would harbor antagonistic microbiota capable of reducing weed pressure to an agronomically-significant extent[16–18]. Weed suppression might be exerted by microbes typically viewed as pathogens[13], but strong antagonistic effects can be also be directly exerted by AMF on non-host plant species, including certain important field-crop weeds[19–25]. The mechanistic basis of such antagonistic effects has not been established, but may involve induction of necrosis in seedlings of non-host species[19].

In addition to reducing weed abundance through 'weed suppression', interactions with soil microbiota may affect diversity and distribution of biomass in weed communities. It is now thought that the predominant

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effect of plant–soil microbe interactions is to increase plant community diversity[26–28]. At least two mechanisms can lead to this outcome: negative plant–soil feedback processes can limit abundance of potentially dominant species[3], and increased microbial diversity and abundance can support plant diversity by providing essential mutualists to increasing numbers of plant species[29–32]. Microbial effects on weed community diversity are of interest because such diversity may significantly affect a variety of important properties of field-crop agroecosystems, including capacities for soil nutrient cycling and biodiversity conservation[33–37].

However, very little is known about interactions of field-crop weeds with soil microbiota under field conditions. In the study reported below, we addressed this knowledge gap by manipulation of certain soil microbiota in experimental weed communities established in corn and soybean crops, applying a soil fungicide to reduce diversity and abundance of soil fungi. We used a fungicide, benomyl, which has been used extensively for this purpose in other ecosystems. Benomyl has been repeatedly shown to alter soil fungal communities, to thereby affect plant population and community processes, and to primarily affect AMF[38]. Moreover, it has been shown to have only modest artifactual effects on nutrient cycling and non-fungal soil biota[39,40], and, overall, to have fewer drawbacks than other methods for manipulating soil fungal communities in large-scale field experiments[38]. From current understanding of AMF–plant interactions, we hypothesized that suppression of this group of soil fungi would change the composition of experimental weed communities in corn and soybean crops, reduce performance of AMF-host weeds relative to non-host species, and reduce diversity and evenness in these weed communities.

Materials and Methods

Field experiments

All field experiments were carried out at the University of Minnesota Experiment Station (Rosemount, MN, 44° 41′N, 93° 04′W, well-drained Waukegan silt loam). The experimental field was planted with a cover crop (winter rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), field pea (*Pisum sativum* L.)) in autumn 1999; then, in spring 2000, cover-crop regrowth was suppressed with glyphosate applications and rototilling. Permanent plots (2 m × 3 m) were marked and benomyl fungicide (Benlate SP; E.I. du Pont de Nemours and Co., Wilmington, DE) applications were begun on 25 May 2000. Fungicide was applied as a soil drench at 2.5 g a.i.m^{-2}; control plots received equal amounts of water. Fungicide applications were made at biweekly intervals until 17 July 2000. Plots were planted with a no-till drill on 7 May 2001; these same plots were rototilled by hand tiller and planted with a no-till drill 17 May 2002. Biweekly benomyl applications to plots receiving fungicide resumed immediately after tillage. In 2002, benomyl rate was increased to 3.75 g a.i.m^{-2}, because the previous rate (2.5 g a.i.m^{-2}) had weak effects on AMF infection rates in 2001 (see Table 3). Soybean (*Glycine max* (L.) Merr. 'Surge') and corn (*Zea mays* L. sethoxydim resistant) were planted on 7 June 2000, 29 May 2001 and 17 June 2002; soybean was sown in rows (20 cm spacing) with a conservation tillage drill, while corn was sown with a standard drill in 76 cm rows.

Due to logistical constraints on crop planting operations, we conducted two separate experiments in adjacent sections of the experimental field. One experiment had the crop sequence soybean/corn/soybean in 2000, 2001 and 2002, respectively, while the other experiment followed the sequence corn/soybean/corn in the same years. In each experiment, fungicide or control treatments were applied to plots in a randomized block design with 10 replicates; plots received those same treatments in 2000–2002. No nutrients were applied to plots, as recommended by soil tests (based on 20 5 cm by 15 cm soil core samples collected systematically across the experimental site). At the start of the experiment, soils contained 4.3% organic matter, 33 μg g^{-1} available P (Bray 1 test), 67 μg g^{-1} potassium, 3.3 μg g^{-1} NO_3-N, and had a pH of 7.2. In 2000 and 2001, certain grass weeds (not part of experimental weed communities) were highly abundant in experimental plots; in accordance with standard agronomic practice, these weeds were suppressed by a selective grass herbicide application (Poast, BASF, Floram Park, NJ) on 22 July 2000 and 28 June 2001 to all plots at a standard rate (2.34 l ha^{-1}). In 2002, grass weeds were less abundant and no herbicide was applied.

Weed seeds were sown in the entire area of each plot immediately after crop planting. In 2000, laboratory germination percentages were used to determine seeding densities (Table 1) sufficient to achieve an expected seedling density of 125 m^{-2}, evenly divided between AMF-host and non-host species. In 2001 and 2002, sowing densities were increased to an expected seedling density of 175 seedlings m^{-2}, again evenly divided into AMF-host and non-host species (Table 1). Heavy rains occurred after weed planting in 2001 and emergence of most species was very limited; accordingly, all species were replanted at the same seeding rate on 26 June 2001. After planting, a 0.5 m^2 subplot was marked within each plot, and all seedlings of sown experimental weed species within this subplot were marked. In each plot, surviving weeds were counted and aboveground biomass harvested when most weed species were beginning to flower (15 August 2000, 21 August 2001, 28 August 2002). Biomass was oven-dried and weighed from 3 to 7 days at 60°C.

In 2000 and 2002, aboveground biomass of each crop was estimated at the time of weed biomass harvest by clipping a sample of crop plants at soil level. In soybean plots, soybean plants within a section (30 cm) of row were harvested; in corn plots, three plants were harvested. Crop biomass was oven-dried and weighed. In 2001, crop biomass was harvested on 19 September 2001.

Table 1. Seeding rates (seeds m^{-2}) and composition of experimental weed communities.

Weed species	2000	2001	2002
AMF-host			
Abutilon theophrasti	10	10	10
Ambrosia artimisiifolia	20	20	20
Cirsium arvense	10	10	10
Euphorbia maculata	30	30	30
Galium aparine	5	5	5
Hibiscus trionum	10	0	0
Malva parviflora	5	5	5
Plantago lanceolata	80	80	80
Sida spinosa	5	10	10
Solanum nigrum	40	40	40
Solanum ptycanthum	0	40	40
Non-host			
Amaranthus retroflexus	20	20	20
Brassica nigra	5	10	10
Chenopodium album	80	80	80
Lepidium campestral	5	5	5
Mollugo verticillata	30	30	30
Polygonum lapathifolium	40	60	60
Portulaca oleracea	20	20	20
Rumex crispus	5	10	10
Thlaspi arvense	5	0	0

AMF colonization assays

In 2000 and 2001, root samples of the strong AMF host *Ambrosia artimisiifolia* L. (AMBEL, see Table 3) were collected by plot in late summer to assess fungicide effects on AMF colonization levels. In 2002, in addition to *A. artimisiifolia*, root samples of soybean and several additional weed species (*Abutilon theophrasti* Medik. (ABUTH), *Sida spinosa* L. (SIDSP), and *Solanum nigrum* L. (SOLNI)) were collected at the time of weed biomass harvest to assess mycorrhizal colonization. In all years, plant roots were held on ice after collection, then cleaned and frozen. Roots of each species were subsampled and stained with aniline blue[41]. Roots were examined microscopically (200×) to assess mycorrhizal root colonization (hyphae, arbuscules, and vesicles) using the magnified intersection method[42].

Disease assays

Soil from the Rosemount Experiment Station was collected and stored in a cooler for 3 months. At time of planting, soil was evenly mixed 1 : 3 : 3 soil : sterile sand : vermiculite (approx. 14% inoculum). This mix was placed in clean pots (3.8 × 18 cm). Seeds of five weed species (*Abutilon theophrasti*, *Amaranthus retroflexus* L., *Ambrosia artemisiifolia*, *Chenopodium album* L. and *S. nigrum*) were surface-sterilized (5% sodium hypochlorite) for 5 min and rinsed well, planted, and covered with additional vermiculite. Pots were arranged in a randomized complete block with 5 species × 2 treatments × 10 replicates = 100 pots. Germinating seedlings were thinned to 1 seedling pot^{-1}. At 10 and 24 days after planting, benomyl was applied to half of the pots at a standard rate of 2.5 g a.i.m^{-2}; water was applied to the remaining (control) pots. All pots were watered daily for 5–6 weeks. After 6 weeks, plants were harvested for biomass and roots were scored for disease incidence/severity by an experienced observer. Roots that were blemish-free and not discolored were classified as non-diseased; roots classified as diseased showed discoloration and lesions consistent with microbial infections by common soil-borne pathogens (*Fusarium*, *Phytophthora*, *Pythium*, etc.).

Statistical analyses

Separate analyses were carried out for each year of the study (2000, 2001 and 2002), because of substantial differences among weed communities establishing in each year, despite nearly uniform seedling treatments (Table 1). Multi-response permutation procedure (MRPP) was used to test fungicide effects on weed community composition; MRPP provides a robust non-parametric alternative to MANOVA[43]. ANOVA was used to test fungicide effects on weed community attributes (total density, biomass and diversity). Mixed-model ANOVA was used to test differential effects of fungicide treatment on AMF-host and non-host weed species; species within each category was considered as a random factor. All ANOVA analyses were done with SAS[44]; MRPP was done with Pcord version 4 (http://home.centurytel.net/~mjm/pcordwin.htm; visited 4 August 2006). Crop biomass production was used as a covariate in most ANOVA analyses, to focus analysis on direct effects of AMF on weeds, rather than effects mediated through crop growth.

Results

Weed community attributes

Fungicide applications had little effect in the first year of application (2000, data not shown), but significantly affected weed density and biomass during the second (2001, Fig. 1) and third (2002, Fig. 2) experimental years. In the second year, fungicide increased total weed density by 34% in corn ($P = 0.039$, ANOVA), but only slightly in soybean; total weed biomass was not significantly increased in either crop. Total weed density in the third year was moderately increased by fungicide in both crops but only the soybean effect approached significance ($P = 0.056$, ANOVA). Fungicide increased total weed biomass in corn by 49%, but had little effect in soybean.

Fungicide also affected weed community composition in the second (Fig. 3) and third years (Fig. 4). The distribution of density among weed species was altered by fungicide in corn in the second year (Fig. 3a; $P = 0.013$, MRPP), and a similar but marginally non-significant effect occurred in soybean in the third year (Fig. 4b; $P = 0.10$, MRPP). The distribution of biomass among species was affected by

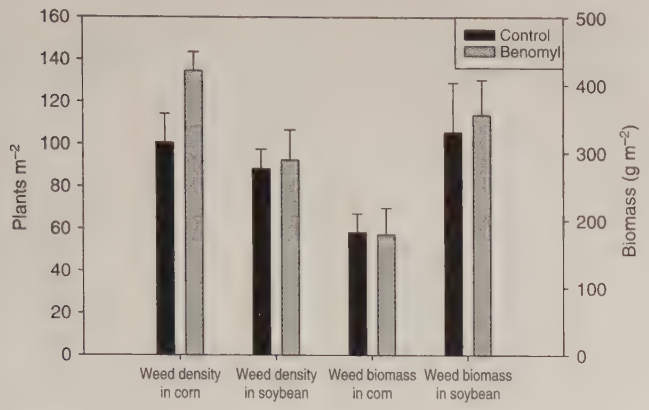

Figure 1. Fungicide effects on total density and biomass production of experimental weed communities in corn and soybean crops in 2001, with standard errors.

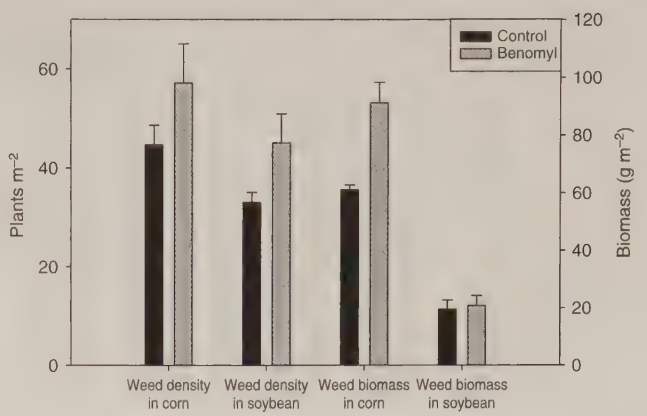

Figure 2. Fungicide effects on total density and biomass production of experimental weed communities in corn and soybean crops in 2002, with standard errors.

fungicide in the corn crop in the third year (Fig. 4c; $P = 0.014$, MRPP). In both years, fungicide effects on both density and biomass production were manifest as modest responses (Figs 3 and 4) in most of the 11 and 6 weed species analyzed in second and third years, respectively. Diversity (Shannon–Weiner)[45] values were calculated for weed communities developing in the second and third years. Calculations were based on the same weed species in all plots (11 and 6 in second and third years, respectively) and therefore treatment effects on diversity indicate effects on the evenness of the distribution of density or biomass among weed species. Fungicide did not significantly affect weed community diversity (Table 2), except in corn in 2001, where fungicide caused the distribution of weed density to become more uneven ($P = 0.02$, ANOVA).

Relative performance of AMF-host and non-host species

In the second year, fungicide application did not significantly affect relative performance of the two classes of weeds (Fig. 5). In the third year, strong effects were evident in soybean (Fig. 6), where fungicide significantly reduced the performance of AMF-host species relative to non-host species, affecting both density and biomass ($P = 0.004$ for density and $P = 0.01$ for biomass, fungicide by species type interactions, ANOVA). AMF-host species were less dense than non-hosts in both treatments, and fungicide increased the differential: AMF-host density was 80% of non-host density without fungicide, but only 41% with fungicide (Fig. 6a; note log scale). Fungicide also increased the proportional performance of non-host species with respect to biomass production (Fig. 6b). Fungicide reduced relative performance of AMF-host species in the corn crop in the third year as well, but only the effect on density approached significance (Fig. 6a, $P = 0.08$, ANOVA). The observed increases in the relative performance of non-hosts resulted from responses of *A. retroflexus* and *C. album*; note that fungicide caused substantial increases in density of *A. retroflexus* and *C. album* in both second and third years (Figs 3a, 4a and 4b). Most non-hosts were unresponsive to fungicide; for example, the non-host group in the second year included *Brassica kaber* (DC.) Wheeler, *Polygonum lapathifolium* L. and *Portulaca oleracea* L., and neither density nor biomass of these species was affected by fungicide. Therefore, the promotion of the relative performance of non-hosts by fungicide was species-specific, and did not reflect a general response by the non-host species group.

Fungicide effects on AMF colonization

To indicate the effect of benomyl applications on mycorrhiza formation in AMF-host weed species, AMF colonization rate (Table 3) was monitored in *A. artemisiifolia* in each year of the study. Fungicide reduced colonization in all cases, but reductions were moderate and largely non-significant, approaching or reaching significance in 3 of 6 cases. In 2002, colonization was assessed in three additional weed species (*Psida spinosa, Solanum nigra, A. theophrasti*) and soybean. Generally, colonization was only modestly reduced in weed species, but was sharply reduced in soybean ($P < 0.01$, ANOVA). Evidently, fungicide applications did have strong effects on some plant species, but in general only modest reductions in colonization were observed.

Fungicide effects on disease symptoms

In four of the five species examined, the percentage of sampled root length showing visible lesions and discoloration was not affected by fungicide treatment; in velvetleaf, the fungicide reduced infected root length by 40% ($P = 0.02$, *t*-test; data not shown). These results must be interpreted with some caution, because this study was conducted in a glasshouse and did not assess cumulative effects of multi-year fungicide applications. However, these results suggest that fungicide application did not have strong effects on pathogen infection for most weed species

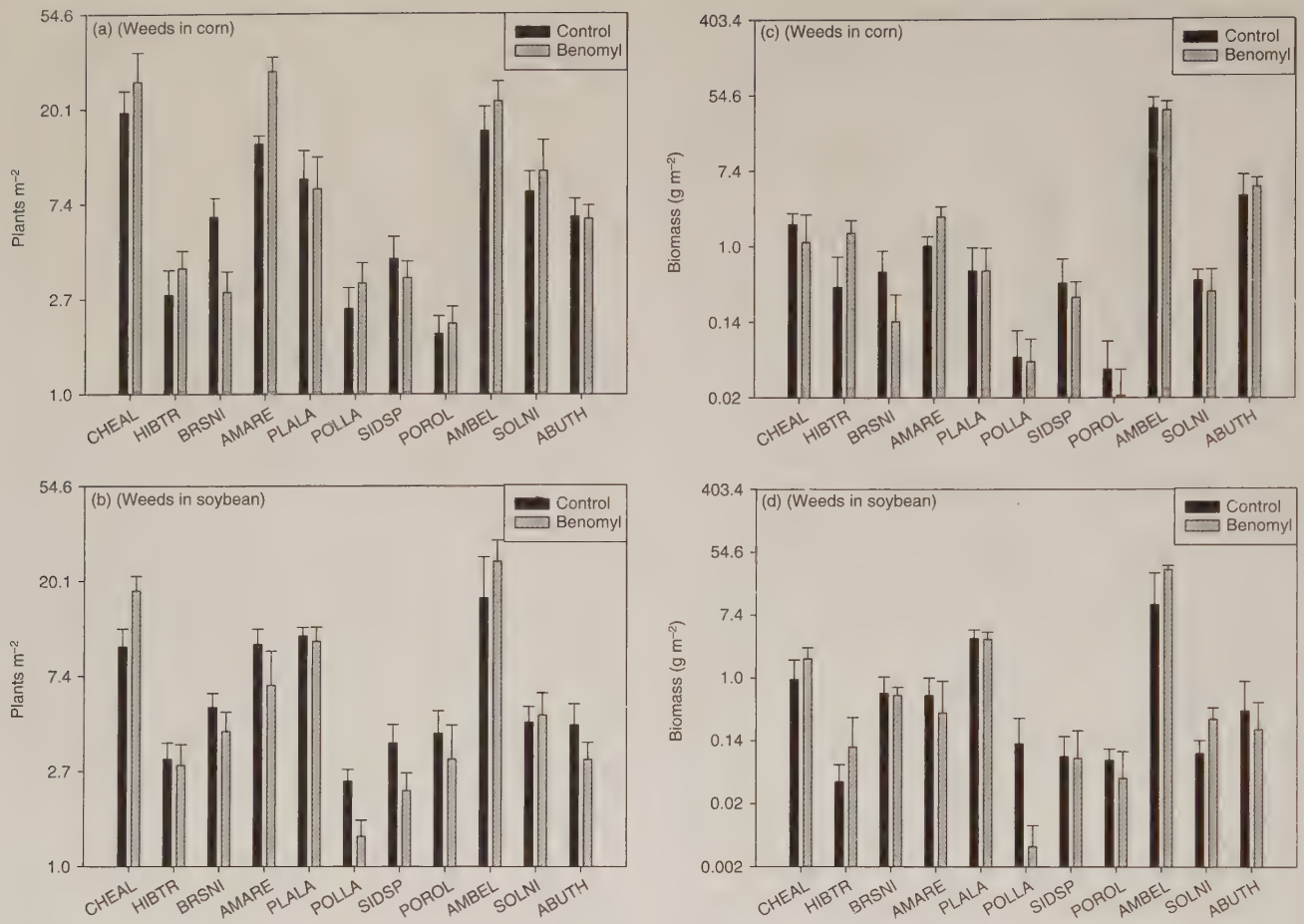

Figure 3. Fungicide effects on weed density (a and b) and biomass production (c and d) by weed species in experimental weed communities in corn and soybean crops in 2001, on natural-logarithm scales, with standard errors. Weed species: *Abutilon theophrasti* (ABUTH), *Ambrosia artimisiifolia* (AMBEL), *Hibiscus trionum* (HIBTR), *Plantago lanceolata* (PLALA), *Sida spinosa* (SIDSP), *Solanum nigrum* (SOLNI), *Amaranthus retroflexus* (AMARE), *Brassica nigra* (BRSNI), *Chenopodium album* (CHEAL), *Polygonum lapathifolium* (POLLA), and *Portulaca oleracea* (POROL).

examined in this study, supporting the inference that fungicide effects result principally from effects on AMF[38].

Discussion

We found that weed density, biomass, community composition and the relative performance of AMF-host and non-host weed species were repeatedly responsive to experimental manipulations of soil fungi, with agronomically significant effects evident after the second and third seasons of fungicide applications. In the second year, fungicide applications were associated with increases in weed density (34% in the corn crop) that significantly increase the risk of substantial immediate yield loss and persistent increases in future weed pressure. In the third year, agronomically significant effects included substantial increases in total weed density (49% in corn) and increases in the relative performance of two non-host weeds (*A. retroflexus* and *C. album*) that are often highly problematic in annual field crop production. These results emerged despite the relatively low power of our experimental design, and suggest that the influence of soil fungi on population and community ecology of field-crop weeds can be large, given that our fungicide application rates apparently caused only moderate reductions in AMF symbiosis with AMF-host weed species (as indicated by colonization levels).

Our findings and results from previous experimental use of benomyl in a variety of plant communities[38,46–48], suggest that suppression of interactions with mycorrhizal fungi was the primary effect of our applications of benomyl fungicide. We note, however, that our observation of weak fungicide effects on disease symptoms does not exclude the possibility that other pathogenic or saprophytic fungi were functionally important to our observed results. With this caveat, our results strengthen a growing base of evidence that AMF can have important influences on the composition, diversity and agroecological functioning of weed communities in field crop agroecosystems. In glasshouse experiments, AMF symbiosis in field crop weeds has been shown to increase growth, seed production and seed quality[49–54], and substantial variation among field-crop weed species in AMF colonization and subsequent growth responses have

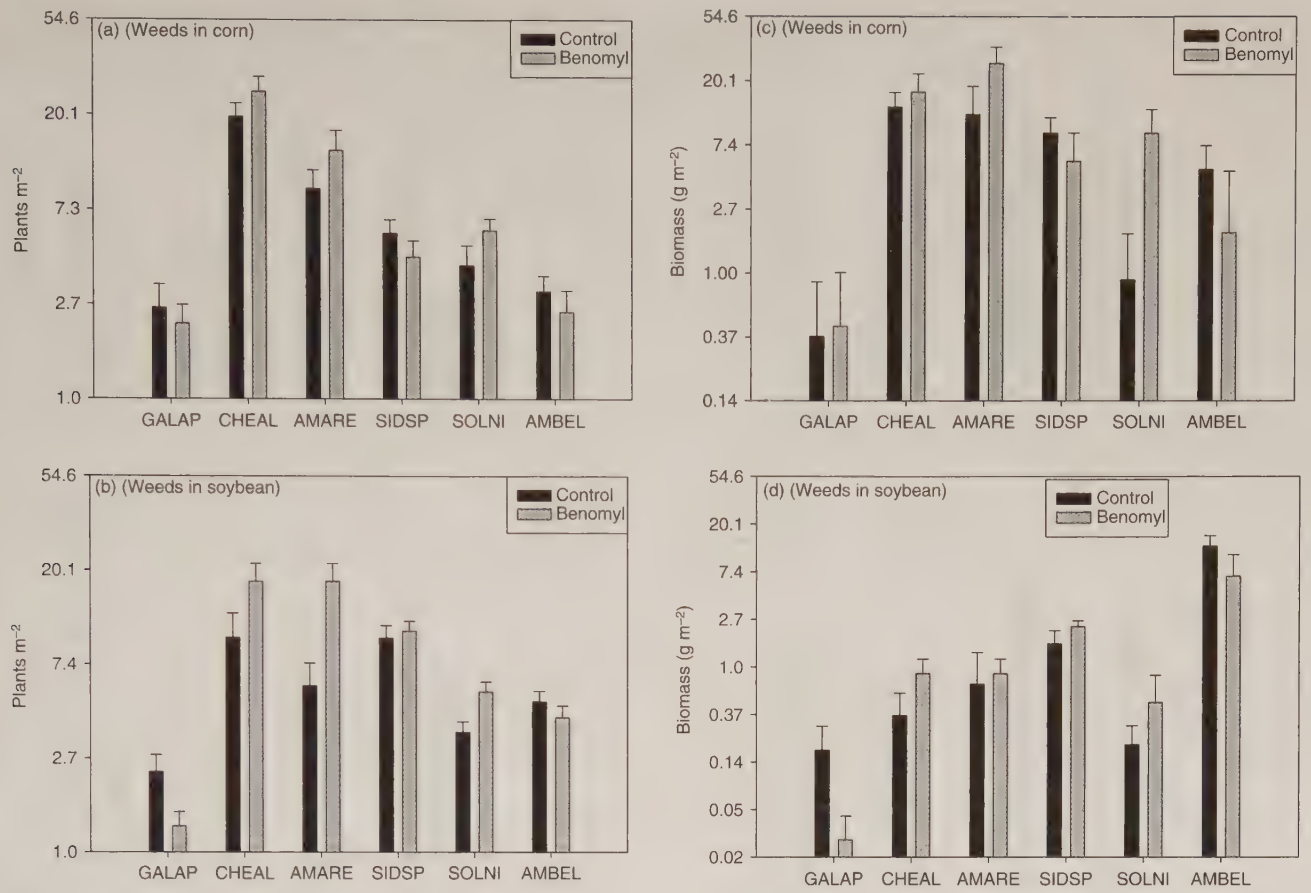

Figure 4. Fungicide effects on weed density (a and b) and biomass production (c and d) by weed species in experimental weed communities in corn and soybean crops in 2002, on natural-logarithm scales, with standard errors. Weed species: *Ambrosia artimisiifolia* (AMBEL), *Sida spinosa* (SIDSP), *Solanum nigrum* (SOLNI), *Amaranthus retroflexus* (AMARE), *Chenopodium album* (CHEAL), and *Galium aparine* (GALAP).

been demonstrated[4]. Given the wide range of biomass responses observed among field-crop weed species, it is possible that AMF could have a substantial effect on the dynamics of weed communities containing these species, particularly in agroecosystems that minimize soil disturbance and mechanical weed control for soil and water conservation purposes. In such agroecosystems, AMF are likely to be more diverse and abundant, and other factors known to affect weed community dynamics (e.g., selective tillage) are likely to be less influential.

We note that fungicide effects often differed between corn and soybean crops, although our design did not permit evaluation of the statistical significance of observed differences. At the close row spacing used in our experiments, soybean crops produced denser and more closed canopies than corn crops. Our observation that weed interactions with soil fungi were apparently modulated by crop species is consistent with previous studies. Mycorrhizal responsiveness among a set of 14 field-crop weeds was generally less positive under reduced light and temperature levels[4], a result consistent with the hypothesis that AMF may typically provide lower net benefits to AMF hosts when photosynthesis is restricted[22]. Thus, although our observations of crop effects on weed–fungi relations must be interpreted cautiously, these results add to evidence suggesting the different sub-canopy environments created by different crop species (or by different planting densities for a single crop) may significantly modulate the effects of soil fungi on weed population and community dynamics. Indeed, AMF interactions with sub-canopy weed plants may be a very important facet of weed–AMF interactions,

Table 2. Shannon–Weiner diversity (SWD) means, with standard error of mean in parentheses, for 2001 and 2002 weed communities; all means based on 10 plots.

	SWD of biomass		SWD of counts	
	2001	**2002**	**2001**	**2002**
Corn				
Fungicide	1.11 (0.13)	1.31 (0.05)	1.78 (0.08)	1.26 (0.08)
Control	1.01 (0.12)	1.31 (0.06)	1.98 (0.05)	1.35 (0.06)
Soybean				
Fungicide	0.99 (0.13)	0.97 (0.1)	1.77 (0.04)	1.39 (0.04)
Control	1.04 (0.14)	0.76 (0.09)	1.82 (0.13)	1.41 (0.05)

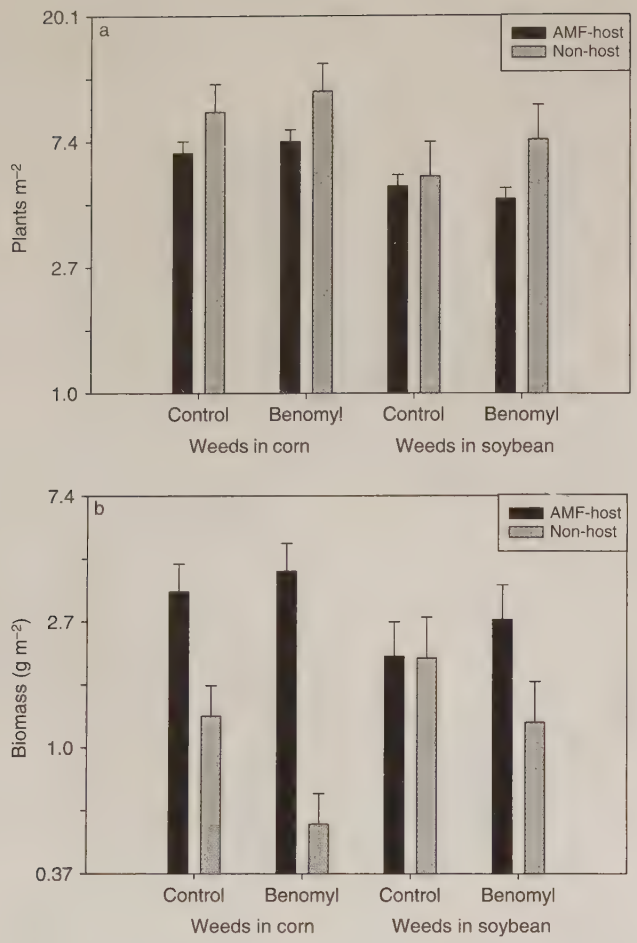

Figure 5. Fungicide effects on the performance of AMF-host and non-host weed species with respect to density (a) and biomass production (b) in corn and soybean crops in 2001, on natural-logarithm scales, with standard errors.

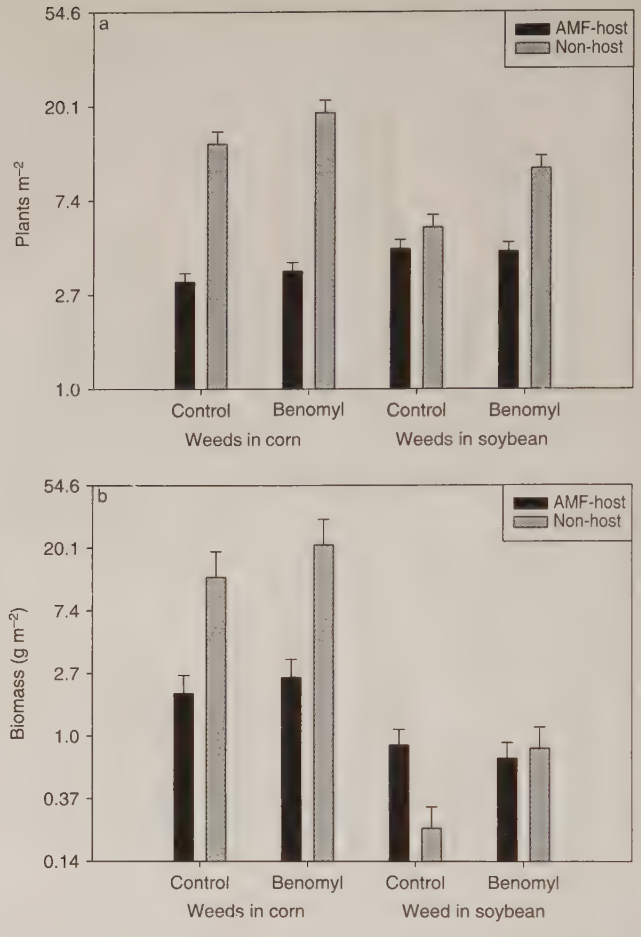

Figure 6. Fungicide effects on the performance of AMF-host and non-host weed species with respect to density (a) and biomass production (b) in corn and soybean crops in 2002, on natural-logarithm scales, with standard errors.

since small, sub-canopy weed plants can produce considerable seed[55] and are probably highly important to population persistence in many weed species

In the third year, we observed a significant increase in relative performance of non-host species when soil fungi were suppressed by fungicide, although this effect was strongly significant only in the soybean crop. A number of mechanisms may underlie such effects[56], including direct antagonistic effects of AMF or other fungi on non-host weed species and indirect effects acting via increased interference with non-host growth by AMF-host species, as a result of interactions with AMF or other fungi. Our findings are consistent with a direct effect. AMF or other fungi may have improved crop growth and thus suppressed weed growth, but we controlled statistically for such effects. Soil fungi might have increased interference effects of AMF-host weeds on non-host species, but in the third year, AMF-host-biomass responses to fungicide were small (except for *Solanum*, for which biomass production was sharply increased by fungicide) and therefore presumably interfered with non-host species less strongly in the absence of fungicide. We note that our results must be interpreted cautiously as the 2002 analysis addressed a relatively limited number of weeds (six species), due to limited weed establishment in that year. Therefore, our results may reflect idiosyncratic responses of these species to soil fungi rather than agroecological differences between AMF-host and non-host weed species. With these caveats, our findings provide results from a field-crop agroecosystem consistent with a substantial number of independent previous studies that have observed powerful direct antagonistic (i.e., pathogenic) effects of AMF on a number of non-host species, some of which are important agronomic weeds[19,22–25]. For example, relative growth rate and survivorship of *C. album* was reduced by 42 and 33%, respectively, when grown with AMF[19]. Many problematic agricultural weeds belong to families that are typically non-hosts[19,57]. Therefore, these observations of antagonistic effects of AMF on non-host species raise the possibility that AMF could provide a broad-spectrum biocontrol measure against non-host weed species. It is also possible that general increase in the abundance of AMF-host weeds would occur in AMF-enhanced cropping systems.

Table 3. Fungicide effects on AMF colonization levels in roots of selected weed species and soybean, given as percentage of AMF presence observed in 100–140 views/root sample; *n* is number of examined root samples, with standard error of mean in parentheses. Weed species: *Abutilon theophrasti* (ABUTH), *Ambrosia artimisiifolia* (AMBEL), *Sida spinosa* (SIDSP), and *Solanum nigrum* (SOLNI).

	2000	2001	2002				
	AMBEL	AMBEL	AMBEL	SOLNI	SIDSP	Soybean	ABUTH
Corn							
Fungicide	70 (3.2)	39 (4.8)	36 (7.0)	14 (2.0)	10 (2.0)		22 (5.0)
n	10	10	4	9	8		9
Control	72 (3.9)	49 (3.1)	40 (3.0)	19 (4.0)	11 (2.0)		27 (3.0)
n	10	10	4	7	10		8
t-test	NS	$P>0.09$ (NS)	NS	NS	NS		NS
Soybean							
Fungicide	42 (4.3)	27 (2.7)	29 (4.9)	12 (5.3)	3 (1.0)	9 (2.0)	21 (2.0)
n	10	10	8	4	3	10	10
Control	65 (5.0)	38 (5.9)	42 (8.9)	1 (1.4)	10 (2.0)	33 (7.0)	21 (3.0)
n	10	10	9	2	4	9	7
t-test	$P>0.0035$	$P>0.10$ (NS)	NS	NS	$P>0.09$ (NS)	$P>0.01$	NS

As we have noted in the present paper, a substantial number of independent studies (cited herein) have observed quite powerful antagonisms of this sort in a variety of plant communities.

Experimental suppression of soil fungi also caused certain changes in weed community composition that were not evidently related to AMF antagonism to non-host species and consequent changes in relative performance of AMF-host and non-host weed species. In the third year, per individual biomass production by the AMF-host species *Solanum* was sharply increased by fungicide in the corn crop, and more weakly so in the soybean crop. Since fungicide caused AMF colonization to decline by ca. 25% (albeit non-significant, Table 3), this response may reflect a negative growth response to AMF symbiosis[58,59], although its magnitude is larger than most such responses observed to date, or the pathogenic effect of non-AMF fungi. Similarly, in the second year, fungicide significantly affected the distribution of density among weed species in the corn crop but without any indication of differential responses among AMF-host and non-host species. Among 11 weed species, responses were (at most) modest in all but two species; these were both non-hosts (*Brassica* and *Amaranthus*) but showed opposite responses to fungicide.

Our field experiment shows that soil fungi can decrease weed density, biomass and the relative abundance and growth of both AMF-host and non-host weed species. If such effects occur widely in field-crop agroecosystems, there are a number of implications for weed management. First, antagonistic fungal effects (such as that suffered by *Solanum* in the third year) might serve as one of the 'small hammers' by which agroecological processes limit weed abundance and interference with crop production[60]. Such interactions may be of considerable significance in the context of integrated weed management systems. Typically, only a few weed species are well-enough adapted to the management factors operant in any particular agroecosystem to become highly problematic in that system. Antagonistic fungal effects on these species could be very useful in their management.

Moreover, in addition to potential value to integrated weed management, interactions between weeds and soil fungi may affect weed diversity. Theory and limited empirical evidence suggest that if management factors serve to intensify weed interactions with soil fungi, the diversity of weed communities may be increased[26,27,61], although we found only limited evidence of this outcome. If negative effects on crop yield or otherwise are acceptably small, increasing weed diversity may provide a useful option for restoring useful microbial biodiversity in field-crop agroecosystems, given mounting evidence that diverse weed communities provide certain agroecological 'services'[36,37,62] that are relevant to both production and conservation in agroecosystems. For example, AMF-host weeds may benefit crop production by maintaining diversity and abundance of agronomically beneficial AMF taxa; removal of AMF-host weeds from agroecosystems can cause changes in diversity, abundance and functioning of AMF, and can reduce beneficial AMF effects on crop growth[63,64]. Diverse weed communities may provide a range of other services, including increased interference among weed species that may reduce herbicide resistance risk[37], and maintenance of valued wildlife species and predatory and pollinating arthropod species in certain agroecosystems[34,36].

Taken together, indications of the significance of weed–soil fungi interactions for weed management and ecological services from weeds, and our finding that these interactions can be strong under field conditions, should encourage further investigations of weed–fungi interactions in field-crop agroecosystems. Such work is particularly warranted in cropping systems where conservation tillage and cover

cropping techniques have been practiced for some time. Weed–fungal microbe interactions are likely to be generally stronger in such situations; if these interactions have real agronomic importance, it will likely be in such agroecosystems.

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Effects of soil fungi on weed communities in a corn–soybean rotation – ADDENDUM

Authors' response to review comments

N. Jordan and S. Huerd

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At the Editor's suggestion, we are including a set of thoughtful review comments from one of our reviewers on the first revision of our manuscript, and our responses to the reviewer's comments.

Reviewer 1: Although the author's revision has improved the manuscript to some extent the primary criticism on the original manuscript has not been addressed adequately. The authors' decision to keep highly speculative (conclusive) statements in spite of minor and variable evidence supporting their hypothesis only undermines the quality of the discussion and the paper. For example, authors discounted the effects of fungicides on fungal diseases based on one glasshouse trial which showed variable result. The effects on AMF were also variable and moderate. Statements suggesting AMF as a potential biocontrol measure do little to support the main hypothesis of the study. Authors have not discussed the role of fungicide effects on nutrient availability when discussing the growth of weed species.

Overall there needs to be further modifications to the discussion section to focus on the main objective in order for this paper to be acceptable for publication.

Essentially, we see three issues raised in reviewer 1's comment:

I. Are we overstating our results with respect to the 'main objective' of our experiment, namely to assess whether soil fungal communities can have effects on field crop weeds that are significant in agronomic and agroecological terms?

The reviewer expressed concern that our conclusions are 'highly speculative', and that our results provide only 'minor and variable evidence supporting their hypothesis'. Of course, whether evidence is 'minor and variable' is a matter of opinion, but we believe that our findings do reveal that soil fungi can have significant effects on weeds.

If we discount results from the first year of fungicide treatments (a variety of other studies show that benomyl effects on soil fungi are cumulative and therefore we did not expect a substantial biological response after the first season of fungicide applications), then our results can be summarized as follows:

- Significant effects first appeared after the second season of fungicide applications, and a wider range of effects was evident in the third year.
- In the second year, there was essentially only one significant fungicide effect, but this was not 'minor' in agronomic terms: fungicide caused a 34% increase in total weed density in the corn crop, with associated effects on the composition and evenness of the weed community. Such an increase in weed density creates the potential for significant loss of yield, and for significantly increased weed pressure in the future.
- In the third year, fungicide caused effects in both crops that again are not 'minor' in agronomic terms. In corn, total biomass increased by 49%, an increase with significant implications for yield and future weed pressure, and there were associated effects on weed community composition and on the relative performance of host and non-host weeds. In soybean, there were large changes in the relative performance of these two weed classes, which was associated with large changes in the performance of two non-host weeds that can pose major management problems in corn–soybean production systems (lambsquarters and redroot pigweed).

Furthermore, a number of aspects of our design, especially the use of a fungicide known to be only partially effective on AM fungi (as demonstrated by the observed effects of the fungicide treatments) make for a relatively conservative test of our main hypothesis. Therefore, our observations of arguably 'non-minor' effects despite conservative aspects of our design further justifies the conclusions that we draw in the discussion section.

Finally, a recent report[1] emphasizes that caution is needed in interpreting fungicide effects on plant communities, but, consistent with our interpretations of our results, does not dispute that the major mechanism of these effects is through changes in plant–fungi interactions. They view the major complication as the question of separating direct and indirect effects of changes in these interactions, as we discuss.

We excerpt our summary statement of findings from the discussion:

Our findings indicate that the population and community ecology of these field-crop weeds can be strongly affected by the fungal component of soil microbiota. This result emerged despite the relatively low power of our experimental design, and suggests that the influence of

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soil fungi on population and community ecology of field-crop weeds can be large, given that our fungicide application rates apparently caused only moderate reductions in AMF symbiosis with AMF-host weed species (as indicated by colonization levels).

We see this statement as well justified, not excessively broad ('... field-crop weeds can be strongly affected ... can be large') and not 'highly speculative'.

II. The second issue raised by the reviewer's comments, we believe, is whether we have erred in attributing the fungicide effects we observed to responses mediated by soil fungi, as opposed to some other artifactual effect(s) of fungicide application. The reviewer identifies one artifactual effect that exemplifies this concern: 'Authors have not discussed the role of fungicide effects on nutrient availability when discussing the growth of weed species'.

We appreciate the potential importance of artifactual effects identified by the reviewer, but we do remain confident in attributing our results primarily to effects on soil fungi in general. First, as we note in the manuscript, there is a significant base of evidence supporting this conclusion from previous work: 'Benomyl has been repeatedly shown to alter soil fungal communities and thereby to affect plant population and community processes, and to primarily affect AMF'. In particular, a number of studies has examined the effects of benomyl applications on other soil attributes that might be relevant to the plant population and community attributes of interest. These have come to a unanimous conclusion that benomyl principally affects fungi, and apparently does not have large artifactual effects. To elaborate:

'The patterns of effects of the fungicides on soil nutrient cycling processes were not large and were specific to each fungicide. Captan appeared to have more pronounced overall effects on soil microbial activity and nitrogen dynamics than either benomyl or chlorothalonil'[2].

'The magnitude of benomyl effects on soil components and processes were small (< 33% change with benomyl) relative to effects on mycorrhizal root colonization (80% decrease with benomyl). These results indicate that rather than having large non-target effects, benomyl applications principally affect mycorrhizal root colonization, thereby indirectly influencing soil biota and nutrient availability'[3].

'It can be concluded that although pesticides had transient effects on microorganisms and, possibly, some microbivorous animals, their influence on nutrient dynamics was negligible and they did not affect plant growth indirectly'[4].

On a related note, the reviewer provides this criticism: 'For example, authors discounted the effects of fungicides on fungal diseases based on one glasshouse trial which showed variable result (sic)'. This is a fair and useful comment, and we have revised the discussion to be more cautious in attribution of observed effects of AMF.

III. Finally, the reviewer remains concerned about our comments in the discussion section regarding the possibility of antagonistic effects of AMF to non-host species, stating that 'Statements suggesting AMF as a potential biocontrol measure do little to support the main hypothesis of the study'.

We wish to clarify that the comments that concern the reviewer do not seem to us to be directly relevant to the veracity of the main hypothesis, but rather represent our effort to interpret the significance and meaning of our findings relevant to that hypothesis. However, in response to the reviewer's concern, we have downplayed the discussion of AMF antagonism toward non-host species, since indeed our results did show that promotion of the relative performance of non-hosts by fungicide was species-specific, and did not indicate a more general response by the non-host species group. We would be reluctant to remove all discussion of this phenomenon, however, as we noted in the manuscript, a substantial number of independent studies (cited in manuscript) have observed quite powerful antagonisms of this sort in a variety of plant communities. Therefore, our suggestion that we may be observing such effects in a field-crop weed community is not 'highly speculative'.

Acknowledgements. We are grateful to Dr Gupta Vadakattu (CSIRO, Australia) who was willing to have his review comments, and our responses to them, published here in this addendum to our research paper (doi: 10.1017/S1742170508002226).

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Weed management in organic echinacea (*Echinacea purpurea*) and lettuce (*Lactuca sativa*) production

P. Kristiansen*, B.M. Sindel, and R.S. Jessop

School of Rural Science and Agriculture, University of New England, Armidale, NSW 2351, Australia.
*Corresponding author: paul.kristiansen@une.edu.au

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Abstract

Weed management is a major constraint in organic production. It can be expensive and time-consuming and severe crop yield losses may be incurred when weeds are not adequately controlled. Research on organic weed management (OWM) in herb and vegetable production is increasing internationally, although in Australia very little work has been done to assess current OWM knowledge among growers, and to test the efficacy and cost effectiveness of the weed management practices used by organic growers. The effect of hand weeding, tillage, hay mulch, pelletized paper mulch (PP) and an unweeded control treatment on weed growth, crop growth and cost effectiveness were evaluated in several field trials on the Northern Tablelands of New South Wales using lettuce (*Lactuca sativa* L.) and echinacea (*Echinacea purpurea* Moench. [L.]). In echinacea, hand weeding, hay mulch and PP reduced weed growth by at least 90% compared with the control, while tillage reduced weed levels by about 50%. The more expensive weeding methods such as hand weeding and hay mulch (AU$9600 and 8900 ha^{-1} respectively) produced higher yields, while the cheaper methods such as tillage ($4000 ha^{-1}) had low crop yields and were therefore 25–50% less cost effective. In lettuce, weed growth was reduced by 96% for hand weeding and PP compared with the control, 85% for hay mulch and 66% for tillage. Weed management was cost-effectively achieved using cheaper weeding methods such as tillage ($985 ha^{-1}) compared with more expensive methods such as hand weeding and hay mulching ($4400 and 7600 ha^{-1} respectively). PP had lower yields and was expensive ($12,500 ha^{-1}) and was usually not cost effective in these trials. The results highlight several important advantages and disadvantages of currently used OWM methods in the field.

Key words: tillage, hand weeding, hay mulch, paper mulch, cost, vegetable production, Australia

Introduction

The lack of effective weed management practices is widely reported to be a major constraint in organic production[1]. In the absence of widely supported production strategies and extension programs usually available in conventional agriculture, organic farmers have devised organic weed management (OWM) solutions based on their own needs and capabilities with support from grower groups and certification organizations, and information from published materials in Australia and overseas. But the effectiveness of many of these systems has not been examined.

In Australia, only a few farming systems trials have been conducted that evaluated the effect of organic and non-organic production systems on crop yield, weed density, soil fertility, costs and other variables[2,3]. These trials have not studied the comparative effects of different weeding methods within a given farming system. A small amount of research has been conducted on specific non-chemical weeding methods in herb or vegetable systems, including mulches[4] and tillage[5], but the economics of weed management methods in annual horticultural cropping in Australia has received little attention[6]. Several overseas studies compared different weeding methods in organic vegetable production, including some that present an economic evaluation of the methods tested[7]. Factors that are considered to have an impact on the relative economic performance of weed control methods include the existing weed density, size of the area to be treated, crop type, cost of labor and the price received for the crop.

This paper reports on a comparative evaluation of the agronomic and economic performance of several weed control methods frequently used in organic herb and vegetable production in Australia. In a survey of Australian

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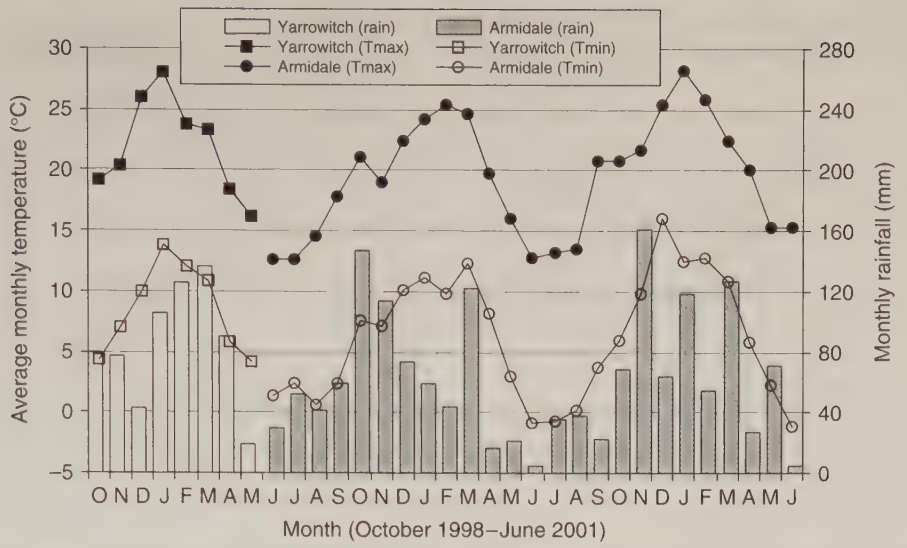

Figure 1. Monthly summaries of average maximum and minimum temperatures and rainfall at Yarrowitch and Armidale for the periods in which the field trials were conducted.

organic herb and vegetable growers, hand weeding (e.g. hand hoeing) was the most common method used (95%), followed by mulching (78%), tillage before and during the cropping season (70%), slashing or mowing to reduce seed set (69%) and crop rotations (65%)[8]. The methods evaluated in the trials reported here (hand weeding, tillage and organic mulches) are also frequently reported in other surveys of organic growers[1]. In addition to hay mulch, a novel pelletized paper mulch (PP) was used in the experiments. PPs have been reported to be effective for weed suppression[9].

A series of experiments was conducted from 1999 to 2001 on two crops with contrasting growth habits, crop growth durations and wholesale values. The medicinal herb, echinacea (*Echinacea purpurea* Moench. [L.]), is widely grown by organic herb growers in Australia[8]. The herb has a relatively high economic value but production is hindered by a long growing season in which weed control is reported to be a serious problem[6]. The salad vegetable, lettuce (*Lactuca sativa* L. cv. Imperial Triumph), in contrast, has a short growing season, forms a smaller canopy and is a less valuable crop. Effective weed control is reported to be more straightforward[10]. The experiments were designed to assess the relative performance of various weed control treatments in terms of weed growth, growth of contrasting crops and treatment cost.

Methods

Trial sites

The field experiments were carried out at three sites over three consecutive summer growing seasons on the Northern Tablelands of New South Wales. In the first year (1998–1999) field trials were conducted at Yarrowitch (31.14°S, 152.00°E, elevation 970 m). This property had been operated organically for the previous two seasons, before which it was used for conventional wool growing. The soil was a granite-derived fine sandy loam (yellow chromosol[11]) with 2% organic carbon and pH 6.0.

In the second year (1999–2000) field trials were undertaken on two of the University of New England's research farms: Kirby Research Station (30.43°S, 151.61°E, elevation 1135 m), and Laureldale Research Station (30.48°S, 151.65°E, elevation 1063 m). Kirby is principally a wool-growing property and the paddock in which the trials were conducted had been sown to pasture and grazed by sheep and cattle for at least the previous 7 years. No herbicides or fertilizers had been used during that time. Laureldale is regularly used for small-plot field trials and has a complex land-use history based on a range of crops and a diverse mixture of fertilizer and pesticide usage patterns. The soil at Kirby was a granite-derived sandy loam (yellow chromosol[11]) with 1.7% organic carbon and pH 5.3, while the Laureldale soil was a basalt-derived chocolate clay (brown dermosol[11]) with 1.8% organic carbon and pH 5.4. In the third year (2000–2001) field trials were not continued at Laureldale due to poor crop growth in the second season, heterogeneity of the site (e.g. variability of weeds), and the high clay content of the soil making access difficult after rain.

The Yarrowitch site was chosen initially as it was a certified working organic farm. When that site became unavailable due to management changes, the trials were conducted on two research farms in the Armidale area with similar climatic conditions but contrasting soil types that are very common in the region. Yarrowitch has a slightly warmer climate with higher rainfall compared with the sites near Armidale, but the soil is similar to Kirby. A summary of the climatic data in Yarrowitch and Armidale during the trials is shown in Figure 1. In the lettuce trials, the rainfall at the Armidale sites in 2000 was lower than Yarrowitch in 1999 and Kirby in 2001. The rainfall at Yarrowitch in 1999 and Kirby in 2001 was similar for the lettuce trials

Table 1. Summary of experiments and the treatments applied in each experiment.

			Weed control treatments				
Site	**Year**	**Crop**	**CO**	**HD**	**TI**	**HY**	**PP**
Yarrowitch	1998–1999	Echinacea	✓	✓	✓	✓	✓
Yarrowitch	1998–1999	Lettuce	✓	✓	✓	✓	✓
Laureldale and Kirby	1999–2000	Lettuce	✓	✓	✓	✓	
Kirby	2000–2001	Echinacea	✓	✓	✓	✓	✓
Kirby	2000–2001	Lettuce	✓	✓	✓	✓	✓

but not the echinacea trials, where rainfall was greater at Yarrowitch compared with Kirby (700 and 400 mm cumulative rainfall respectively).

Experimental design and treatments

Five weed control treatments were assessed, with echinacea and lettuce used as the test crops. The echinacea germplasm was sourced from an organic grower in the region and the cultivar is unknown. Lettuce seed was purchased from a commercial supplier and Imperial Triumph, a crisp head cultivar, was used. Four replicates for each treatment (except lettuce at Kirby, where eight replicates were used) were laid out in a completely randomized design. A control treatment (CO), in which weeds were allowed to grow unchecked, was used to determine the background weed load and the comparative effect on crop yield of doing nothing to control weeds. A hand weeding treatment (HD) was used to test its effectiveness in controlling weeds, and to act as a weeded pseudo-control for determining crop yield in a situation with minimal competition from weeds. Hand weeding was carried out at 4 weeks after planting (WAP) in lettuce and at 4, 8 and 12 WAP in echinacea, and consisted of manually removing weeds using a wheel-mounted stirrup hoe for weeding along the rows and a chipping hoe for removing weeds between crop plants in the planting row. The wheel hoe blade was 230 mm wide and was used at a depth of 50 mm, and the chipping hoe blade was 100 mm wide and used to a depth of 100 mm. The tillage treatment (TI), carried out at the same time as hand weeding, consisted of mechanically removing weeds using a tractor-mounted rigid tine chisel plough. The plough had seven 50 mm wide tines operating at a depth of 130 mm. After each tillage operation, a chipping hoe was used to remove weeds growing in the planting row between the crop plants but not those in close proximity to the crop plants. The hay mulch treatment (HY), predominantly ryegrass (*Lolium* L. sp.) and oats (*Avena sativa* L.), was applied to a thickness of 100 mm (9.5 tonnes ha^{-1}) after planting, and at 4 WAP weeds immediately around the crop plants were manually removed by hand and a further 0.5 tonnes ha^{-1} of hay was added. The PP, composed of pelletized and dried waste paper slurry, was applied to a thickness of 30 mm (42 tons ha^{-1}) after planting. At 4 WAP, weeds immediately around the crop plants were manually removed by hand. The PP was not used in the 1999–2000 trials due to lack of availability. The C : N ratio of the mulches was 39 : 1 and 171 : 1 for hay and paper respectively. A summary of the treatments used in each trial is presented in Table 1.

The experimental plots were prepared using a chisel plough and rotary hoe with the rows being 2 m wide. Echinacea seedlings, aged approximately 8 weeks, were transplanted on October 20, 1998 (Yarrowitch) and November 15, 2000 (Kirby). The seedlings were planted into plots 7 m long in two rows 600 mm apart with a 300 mm spacing between plants along the rows. Lettuce seedlings, aged approximately 3 weeks were planted on December 11, 1998 (Yarrowitch), January 7, 2000 and January 8, 2001 (Kirby and Laureldale 2000). A similar configuration to the echinacea experiment was used but with plots 10 m long. The plants were fertilized by hand after planting with 'Long Life' Dynamic Lifter®, a pelletized poultry manure formulation (nitrogen 4%, phosphorus 3.1%, potassium 1%, calcium 7%, magnesium 0.3%, zinc 0.02 mg kg^{-1} and manganese 0.02%), at a rate of 70 g per plant (700 kg ha^{-1}). Immediately after planting, the seedlings were watered-in using approximately 5 liters of water for each plant. No further irrigation was applied for either crop, which is typical practice for echinacea growers but not lettuce. The echinacea was harvested on March 22, 1999 and April 4, 2001 and the lettuce on February 5, 1999, February 26, 2000 and February 28, 2001.

Measurements

Relative cover, i.e., the proportion of ground area occupied by weeds or crops, was determined using photographs taken above the center of the plots[12,13]. The area captured in the photos was 0.87 m^2 (1.11 m long and 0.78 m wide), including the crop rows and a 250 mm wide strip outside the rows. The photographs were placed under a pane of glass with an etched grid of 28 × 20 cells (6.3 mm sides) and the cells counted according to the predominant ground cover category, either weed, crop, bare ground or mulch. Relative cover was assessed at 2, 4 and 7 WAP in the lettuce trials, and 4, 6, 8, 10, 12, 16, 18, 20 and 21 WAP in the echinacea trials.

Weeds were defined as any non-crop plant growing in the experimental plots. The predominant weed species at each site were recorded, but weeds were not separated by taxon or type. Weed density was measured at crop harvest using a

0.5 m × 1 m quadrat placed lengthwise in the middle of the plot. Weed biomass was measured at harvest by placing a 0.5 m × 1 m quadrat randomly within the plots, cutting all weeds at ground level, drying at 80°C for 72 h and weighing.

Echinacea biomass was determined at 21 WAP by collecting 10 whole plants from the center of the plot, roughly chopping, drying at 80°C for 72 h and weighing. Eight lettuce plants were harvested from the center of each plot at 7 WAP by cutting at ground level and weighing. Gross crop value (GCV) (AU$ ha^{-1}) was calculated by multiplying crop biomass (kg ha^{-1}) by the wholesale price ($ kg^{-1}) The prevailing wholesale prices were $0.58 kg^{-1} for lettuce[14] and $20.00 kg^{-1} for echinacea roots and $4.00 kg^{-1} for echinacea shoots (P. Green, personal communication).

A partial gross margin analysis was conducted to determine the cost effectiveness of weed control treatments. The economic analysis included costs due to the various treatments, with all other variable and fixed costs associated with the production of the crop assumed to be equal. The cost of each weed control treatment ($ ha^{-1}) was based on the amount of materials used, the labor required and machinery usage. Adjusted crop values (ACVs) were derived by subtracting the cost of each treatment at each site from the GCV. The adjusted values provide a measure of the relative cost effectiveness of the treatments in each trial.

The cost for the HD treatment consisted of labor only, while the TI treatment costs included tractor/implement usage, driver's labor and supplementary chipping along the planting rows. The costs of the two mulching treatments were based on the price of the mulch, labor to apply the mulch and labor for supplementary hand weeding at 4 WAP. The costs for machinery and implement usage were obtained from the farm manager at Subiaco Herbs (P. Brown, personal communication) and at Kirby Research Station (N. Thomas, personal communication). There were no costs associated with the CO treatment. Labor was assumed to cost $15 h^{-1}, including 20% on-costs and the mulches cost $110 ton^{-1} and $200 ton^{-1} for hay and paper respectively, not including transport. The amount of mulch required was 8 tons ha^{-1} of hay mulch and 42 tons ha^{-1} of PP. The cost of the TI treatment, including tractor, ploughing implement and the driver's labor, was $48.82 ha^{-1} at Yarrowitch and $56.76 ha^{-1} at Laureldale and Kirby.

To simplify comparisons between sites and years, time was expressed as degree days (°Cd). Degree day estimates were calculated using the single sine method[15], with a base temperature of 4.4°C used for lettuce and 5°C for echinacea[16].

Statistical analysis

Most analyses were carried out using generalized linear models in S-Plus 2000[17]. Diagnostic checks were routinely made regarding distribution of the residuals and dispersion. Significantly different treatment means were separated by contrast analysis. Measurements repeated over a period of time were analyzed with mixed models using SAMM[18] in S-Plus. Time, trial, weed control treatment and their interactions were evaluated as fixed effects while time and plot location within the trials were used as random effects. The suitability of the models was assessed by inspecting the plot of residuals versus fitted values and by observing which random terms increased the log residual likelihood. In addition to linear regressions, non-linear regression was used for several analyzes. Relative weed cover for CO and TI in echinacea was fitted to the logistic function,

$$y = a/(1+e^{(b-x)/c}), \quad (1)$$

where y is the response variable, x is time (degree days), a represents the asymptote, b represents the inflexion point, and c is a scale parameter on the x-axis[17]. Relative echinacea cover was also fitted to Equation 1.

Results

Weed species observed

The weed flora at Yarrowitch was heavily dominated by the three grasses *Digitaria sanguinalis* (L.) Scop., *Paspalum dilatatum* Poir. and *Setaria pumila* (Poir.) Roem. & Schult., with almost no individuals of broad-leaved weeds achieving canopy dominance. At Laureldale, the weed flora was predominantly composed of the broadleaved weeds *Polygonum aviculare* L. and *Hibiscus trionum* L., and the grasses *Echinochloa crus-galli* (L.) P. Beauv. and *D. sanguinalis*. The trials at Kirby were mostly infested with *Acetosella vulgaris* Fourr., *P. aviculare*, *Festuca arundinacea* Schreb. and *Conyza bonariensis* (L.) Cronquist in both growing seasons (2000 and 2001). *Vulpia myuros* (L.) C.C. Gmel. became more common in the second season. The spatial distribution of weed species was highly variable and was not related to the treatments used in the experiment.

Weed growth in echinacea

The response to CO and TI were fitted to a logistic function (Eqn 1), while HD, HY and PP were fitted to a linear equation (Fig. 2). Rapid weed growth was observed in the unweeded CO with 90% cover achieved by about 6–8 WAP. Growth was limited in the TI plots to 40–60% maximum cover. For these treatments, the initial increase in relative weed cover was greater at Yarrowitch which was reflected by lower b (inflection point) values ($b = 286$ and 553 for CO and TI respectively) than Kirby ($b = 448$ and 2287). The HD, HY and PP treatments were effective in maintaining final weed cover levels of about 10% or less. The increase over time was significant for HD in both trials and PP at Kirby ($P \leqslant 0.002$), but the final coverage was still less than 5%. The TI treatment was more variable than the other treatments, as indicated by the larger confidence limits in Figure 2.

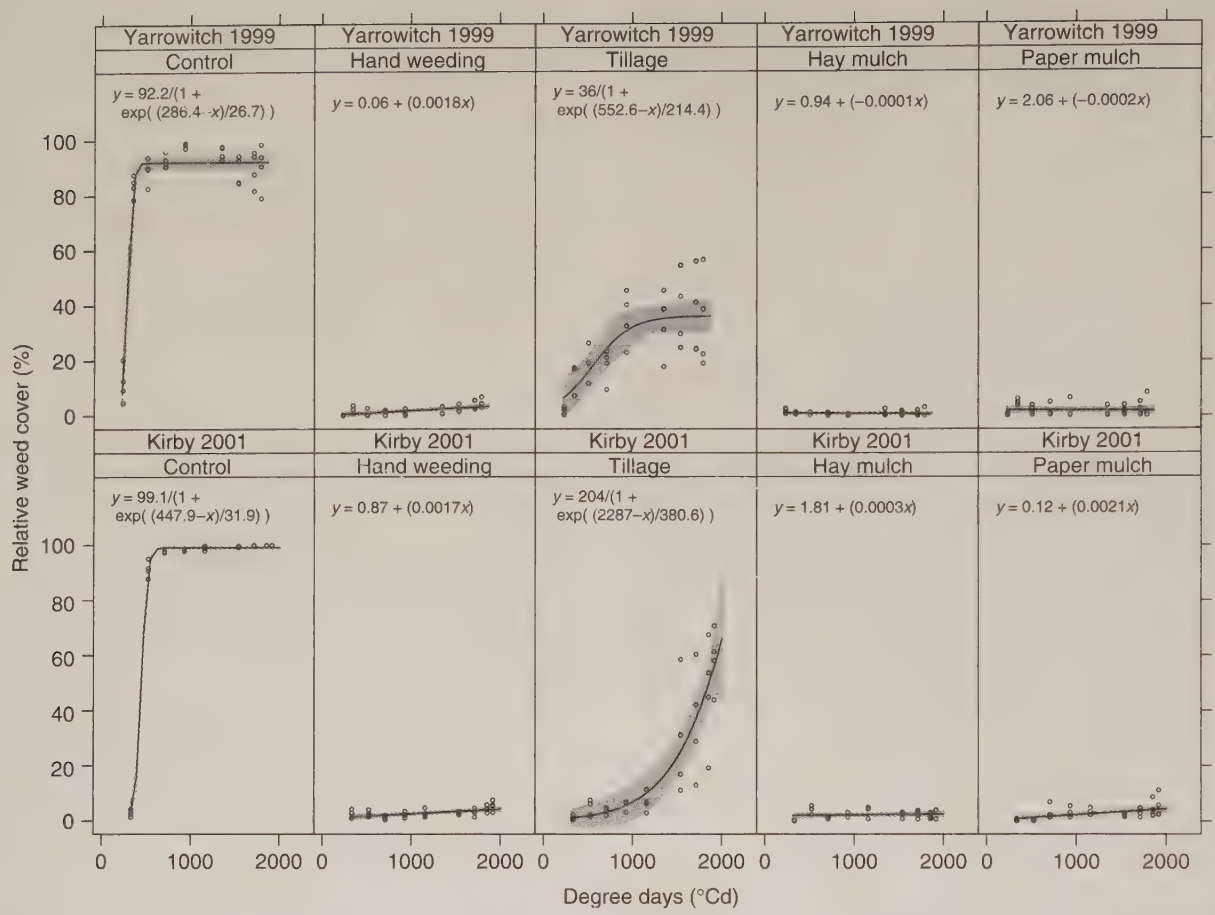

Figure 2. Effect of treatments on relative weed cover in the echinacea trials. The circles show the data points, the solid lines are the regression curves, the shaded area represents the 95% confidence limits and the equations describe the regression for each treatment.

Weed density at echinacea harvest (Fig. 3A) was significantly different at the two sites ($P < 0.001$), partly due to higher rainfall at Yarrowitch. The CO treatment had 930 weeds m^{-2} at Yarrowitch and 560 weeds m^{-2} at Kirby. The treatment effect on weed density was also highly significant ($P < 0.001$), but the interaction between trial and treatment was not ($P = 0.72$). Averaged across trials, the highest densities were recorded for CO (745 weeds m^{-2}) and TI (401 weeds m^{-2}), while HD (85 weeds m^{-2}), HY (72 weeds m^{-2}) and PP (38 weeds m^{-2}) produced similar weed densities ($P > 0.68$). Tillage reduced the density of weeds compared with CO by about 46%, whilst the HD and the mulches reduced weed densities by between 89 and 94%. Weed biomass at echinacea harvest (Fig. 3B) showed the same trends as for weed density. Weed biomass was greatest in CO (11,200 kg ha^{-1} at Yarrowitch and 6500 kg ha^{-1} at Kirby) and moderately high in the TI (average of 3500 kg ha^{-1} for both sites). The final weed biomass of the other treatments, ranging from 150 to 200 kg ha^{-1}, did not differ significantly ($P > 0.88$). A 60% reduction in weed biomass by TI compared with unweeded plots was observed, while HD, HY and PP reduced weed biomass by an average of 98%. Weed density and biomass at echinacea harvest were moderately correlated with relative weed cover across all trials ($R^2 = 0.78$ and 0.72 respectively).

Weed growth in lettuce

In the lettuce trials at Yarrowitch in 1999, Laureldale and Kirby in 2000 and Kirby in 2001, relative weed cover varied significantly between trials and treatments, and the interaction was significant ($P < 0.001$). The weed growth rates for CO at Yarrowitch and Kirby in 2001 ($b \approx 0.11$) were more than double those at Laureldale and Kirby in 2000 ($b \approx 0.05$). The dominant weeds at all sites were annuals, except *A. vulgaris* at Kirby.

Linear regression indicated statistically significant differences in slope; the greatest rate of weed growth occurred in CO, with moderate growth in TI and much lower growth rates in the other treatments (Fig. 4). Weed cover in HD did not increase over time, HY increased significantly in 2000 and 2001 and PP increased in 1999 only.

Weed density and biomass at lettuce harvest (Fig. 5) also differed significantly between trials and treatments, and the interaction was significant ($P < 0.001$), and the density and biomass measurements showed good correlation with relative weed cover ($R^2 = 0.74$ and 0.85 respectively).

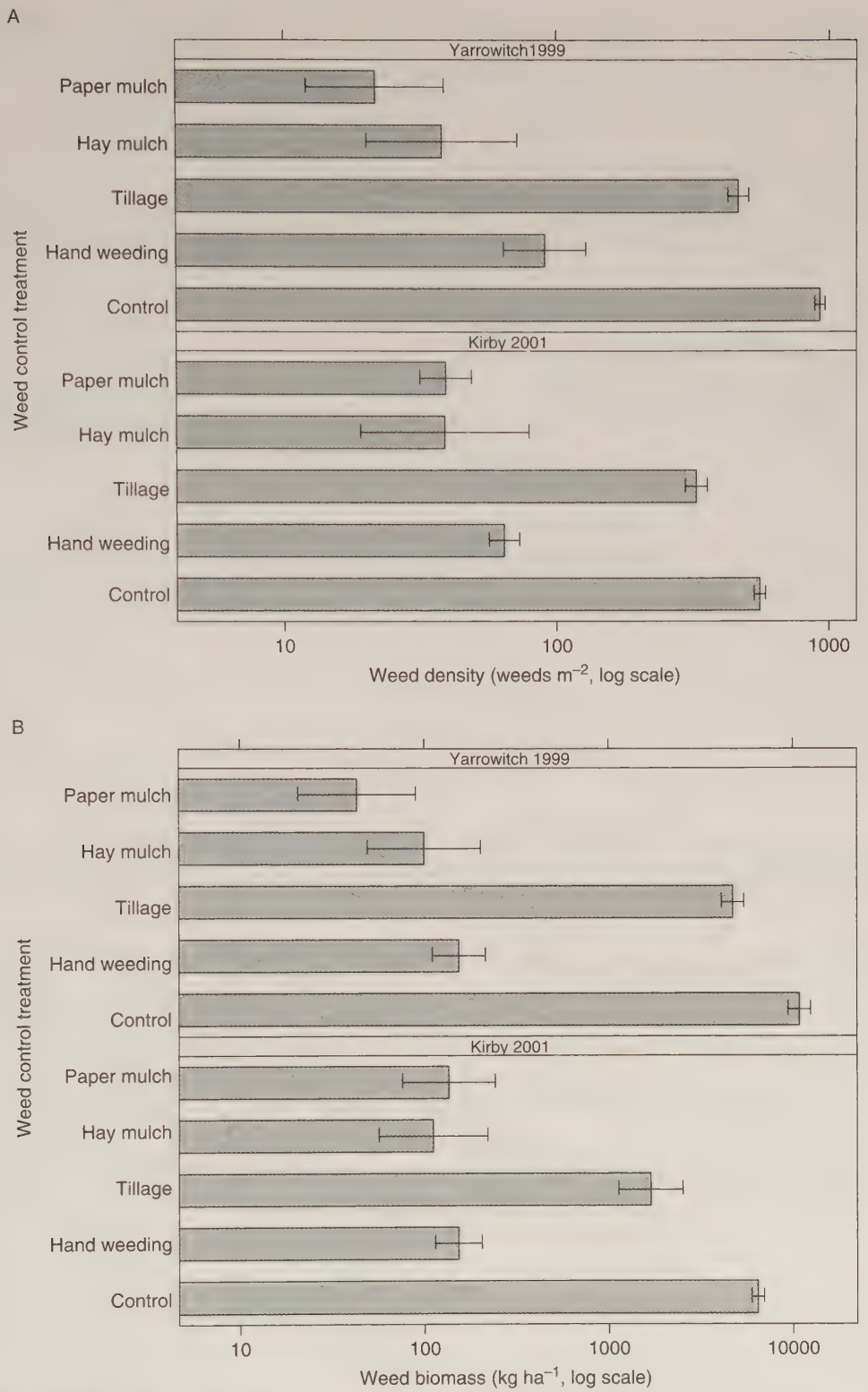

Figure 3. Mean and standard error of weed density (A) and weed biomass (B) in echinacea for the weed control treatments. The data are presented on a log scale.

Density was highest at Yarrowitch (715 weeds m^{-2}), more than double the density at Kirby in 2001 and about 10 times that at Laureldale and Kirby in 2000. Importantly, there was a large increase in weed density between the two seasons at Kirby; from 50 weeds m^{-2} (for CO) in 2000 to 335 weeds m^{-2} in 2001. The CO treatment usually had the highest weed densities, except at Laureldale where it was equivalent to TI and HY, while weed populations were smaller for HD. Averaging the treatments for each trial, the CO yielded 259 weeds m^{-2}, TI 80 weeds m^{-2}, HY

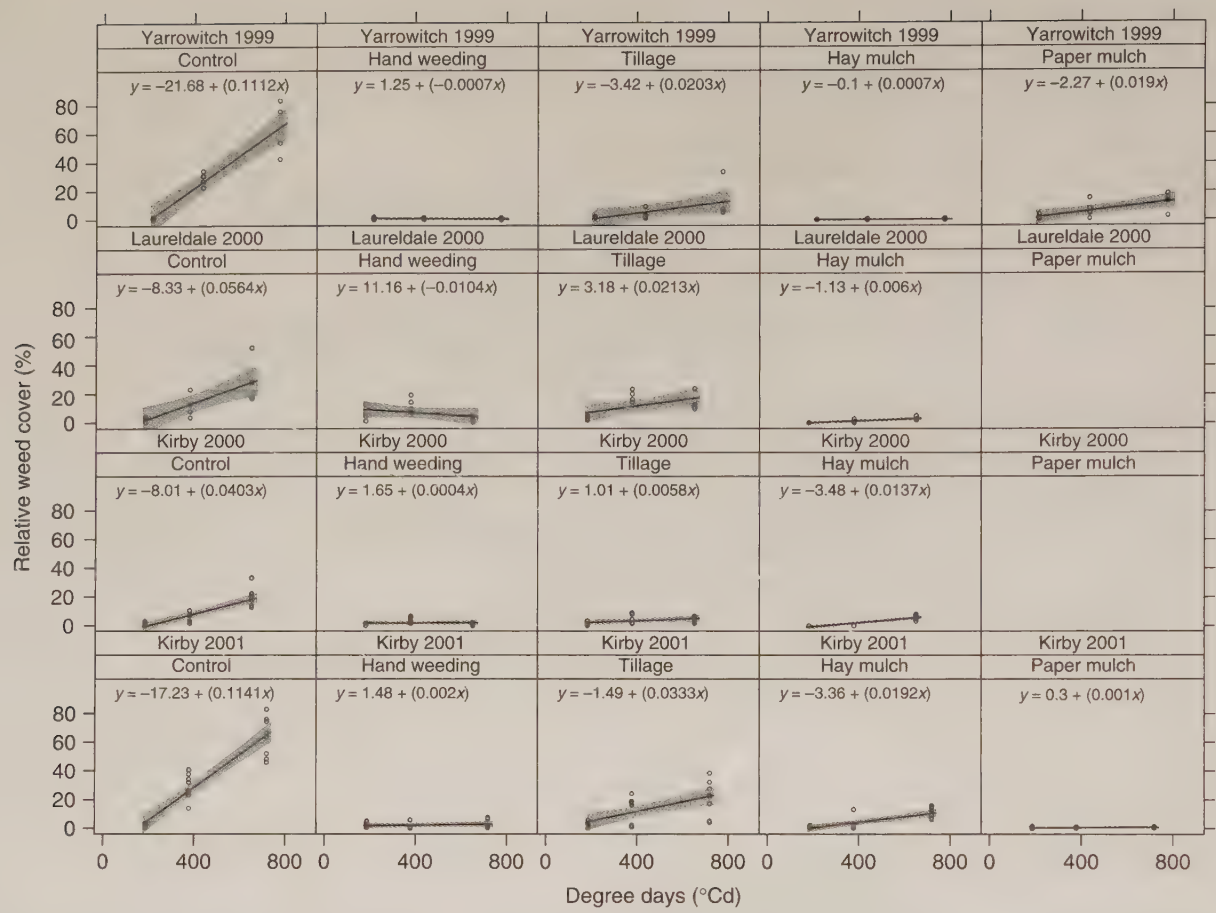

Figure 4. Effect of treatments on relative weed cover in the lettuce trials. The circles show the data points, the solid lines are the linear regression curves, the shaded area represents the 95% confidence limits and the equations describe the regression for each treatment. The PP treatment was not used in 2000.

48 weeds m^{-2}, PP 27 weeds m^{-2} and HD 14 weeds m^{-2}. When weed loads were lighter (e.g., <100 weeds m^{-2} for CO), TI reduced weed density more than when weed pressure was high. This response was not observed for HD, HY and PP, which were more consistent between trials. Weed biomass at lettuce harvest followed a similar pattern to weed density, with CO producing the greatest weed biomass (1450 kg ha^{-1} averaged across trials) and HD the least (59 kg ha^{-1}). Compared with CO, TI reduced weed biomass by 66%, HY by 85%, and HD and PP by 96%.

Echinacea growth

The response of relative echinacea cover to the weed control treatments at Yarrowitch in 1999 and Kirby in 2001 was fitted to a logistic function (Eqn 1). There was very little increase in echinacea relative cover over time for the CO in both trials (Fig. 6). At Yarrowitch, HD and HY reached asymptotes of about 96%, PP reached 86% cover and TI achieved only 62% cover. Echinacea growth at Kirby was considerably lower than Yarrowitch because rainfall was lower by 43% in the second trial. Although echinacea is somewhat tolerant of dry conditions[19], commercial yields clearly require adequate irrigation. HD and HY had the highest crop cover (~65%), while TI and PP had significantly lower relative covers (~25%). An analysis of the effect of cumulative rainfall on relative crop cover showed that echinacea growth was closely related to rainfall ($R^2 \geqslant 0.76$), except in the weedy CO plots with very low crop cover.

Echinacea dry weight at harvest (raw data not shown, see Fig. 8A for derived values) showed similar responses as relative echinacea cover, with significant differences occurring between trials and treatments, and the interaction was significant ($P \leqslant 0.007$). The yields for HD, TI and the mulched treatments at Yarrowitch were similar to commercial yields[6]. Correlation of biomass and relative cover yielded an R^2 of 0.76. Crop biomass was greatest in HD and HY with averaged yields of 7.8 at Yarrowitch and 2.2 tons ha^{-1} at Kirby. TI and PP had significantly lower biomass (average 4.6 and 0.7 tons ha^{-1} at Yarrowitch and Kirby respectively), especially PP at Kirby. Crop biomass production in CO was very small in both trials; 0.6 tons ha^{-1} at Yarrowitch and only 0.06 tons ha^{-1} at Kirby. Compared with HD, there was no significant crop loss in HY, but biomass was reduced by about 50% in TI and PP and 93% in CO.

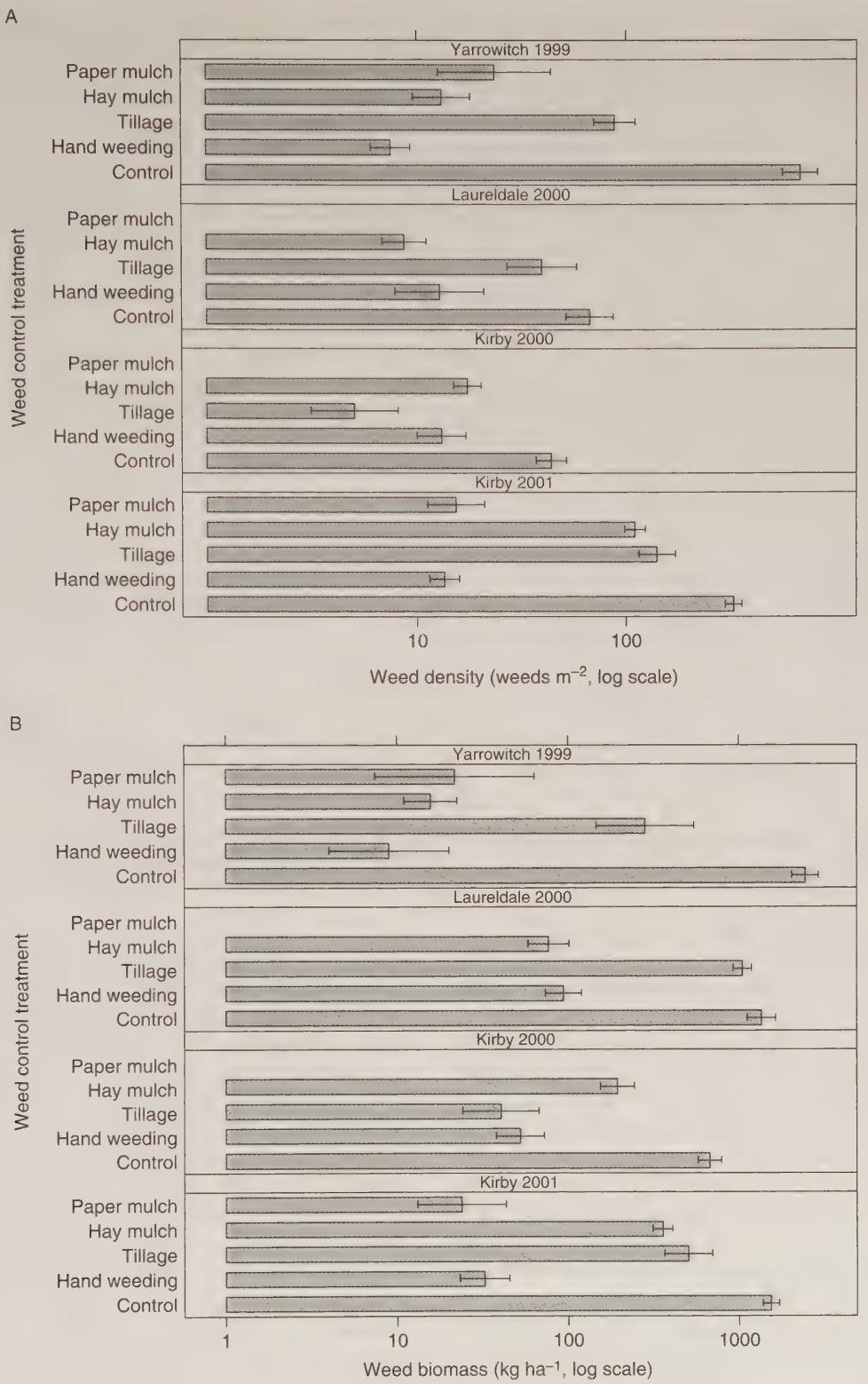

Figure 5. Mean and standard error of weed density (A) and weed biomass (B) in lettuce for the weed control treatments. The data are presented on a log scale. The PP treatment was not used in 2000.

Lettuce growth

The relationship between relative lettuce cover and time was fitted to a linear model (Fig. 7). The treatment effects varied significantly between trials, although HD and HY generally had the highest growth rates (i.e. slope coefficients), PP and CO had the lowest growth rates and TI was intermediate. In 2000 at Kirby, when weed pressure was the lowest, the lettuces in the CO showed equivalent growth to the other weed control treatments ($P = 0.10$). Final relative

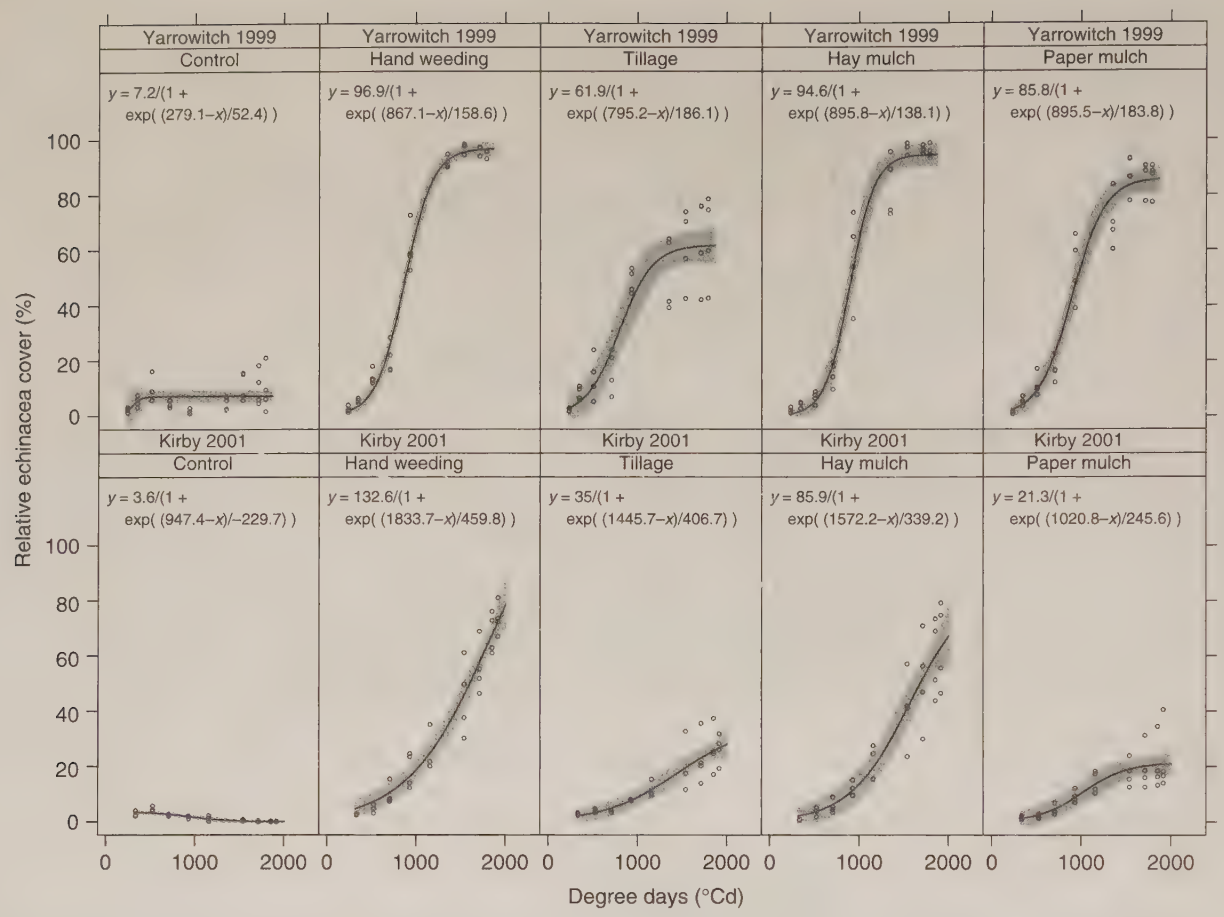

Figure 6. Effect of treatments on relative echinacea cover. The circles show the data points, the solid lines are the logistic regression curves, the shaded area represents the 95% confidence limits and the equations describe the regression for each treatment.

crop cover for HD was greatest at Yarrowitch (~70%), and between 25 and 40% in the other trials. A test of the effect of cumulative rainfall on relative cover indicated that, like echinacea, lettuce growth was affected by rainfall received ($P < 0.001$) and that supplementary irrigation, as used in commercial production, is needed to maintain lettuce yields. Despite the low weed levels in PP (Fig. 4), lettuce growth was reduced in both trials, especially at Kirby. Lettuce fresh weight biomass at harvest (raw data not shown, see Fig. 8A for derived values) had the same treatment rankings across the four trials as relative crop cover, and the two variables had a correlation of $R^2 = 0.66$. Lettuce yields for HD, TI and HY in these trials were similar to commercial yields, despite the lack of irrigation. The highest yields were observed in HD and HY, with lettuce biomass averaging ~23 tons ha^{-1}. Yields in TI were ~13% less than HD and HY ($P \geqslant 0.089$), while CO was reduced by 25% and PP by ~50%.

Weed–crop relationships

The relationship between weed variables (relative cover, density and biomass) and crop variables (relative cover and biomass) at echinacea harvest were assessed using linear regression (Table 2). Relative weed cover at Yarrowitch had the highest R^2 values with the crop variables and weed density was also high. Relative echinacea cover had higher R^2 values with the weed variable than echinacea biomass. The PP treatment had low weed levels but also had lower crop yields, so excluding the PP treatment improved the goodness of fit. At Kirby, the weed cover relationships were weaker, but excluding PP gave R^2 values of 0.67 or higher.

The relationship between weed variables and lettuce yield variables at harvest were low in all trials (Table 3). Some treatments with low relative weed cover had lower lettuce yields (e.g., PP), while other treatments with moderate to high weed levels, such as CO and TI, may have had reasonable yields. Underlying weed levels did not consistently influence the relationships, with lower weed loads at Laureldale and Kirby in 2000 being associated with high and low R^2 values respectively.

Economic analysis

The direct cost of carrying out each weed control treatment is shown in Table 4. The most expensive treatment for both echinacea and lettuce was PP, at a cost of about \$12,500 ha^{-1} (averaged across all trials), of which 65% was due to purchase costs, 30% for laying and <5% for

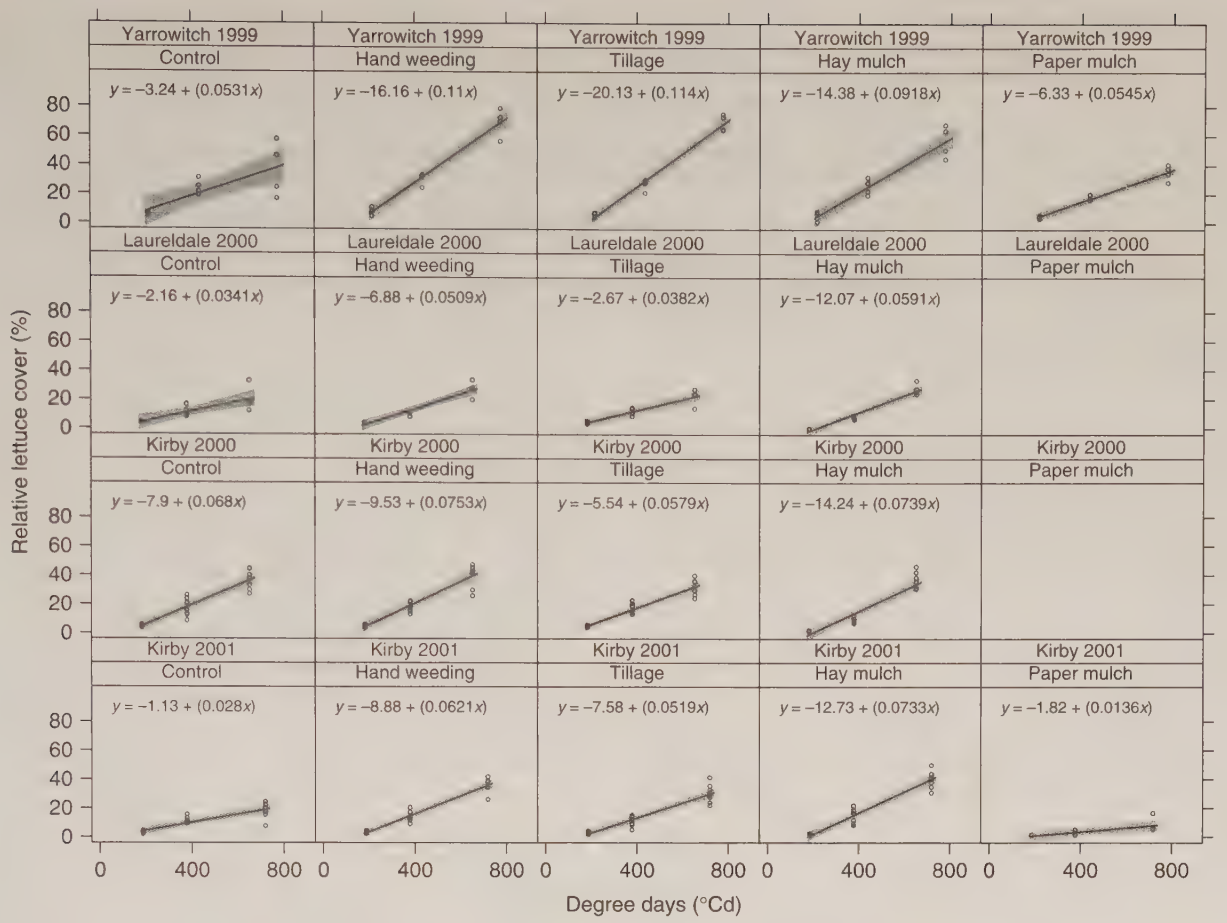

Figure 7. Effect of treatments on relative lettuce cover. The circles show the data points, the solid lines are the linear regression curves, the shaded area represents the 95% confidence limits and the equations describe the regression for each treatment. The PP treatment was not used in 2000.

follow-up hand weeding. In echinacea, the next most expensive treatments were HD at \$9600 ha^{-1} and HY at \$8900 ha^{-1}. The costs for HY were based on purchase costs (14%), laying the mulch (50%) and supplementary hand weeding (36%). In lettuce, the cost of HY remained high (\$7600 ha^{-1}), but the HD costs were considerably lower (\$4400 ha^{-1}). The TI treatment was relatively cheap (\$4000 and \$985 ha^{-1} for echinacea and lettuce respectively), made up of 5% for machinery costs and 95% for labor (tractor driving and supplementary hand weeding). No direct costs were incurred in the control.

The GCV and ACV for echinacea are shown in Figure 8. In Figure 8A, the response pattern for GCV follows that reported for crop biomass, with large differences observed between trials and treatments ($P < 0.001$). HD and HY produced similarly high GCV, averaged at \$49,000 ha^{-1} and \$15,500 ha^{-1} at Yarrowitch and Kirby respectively, whilst the GCV for TI was reduced by half and CO about 90%. PP performed moderately well at Yarrowitch, with a GCV about one third less than HD and HY, but performed poorly at Kirby, with GCV reduced by about 70%. For ACV (Fig. 8B), treatment rankings were unchanged compared with GCV at Yarrowitch, but not at Kirby. In the latter trial, the significantly lower crop growth reduced the yield advantages observed at Yarrowitch. The ACV for HD and HY were equivalent to the cheaper TI treatment but more cost effective than CO ($P \leqslant 0.052$). A loss of about \$9000 ha^{-1} was incurred for PP at Kirby due to the relatively high cost of the mulch and the poor crop yield.

The highest GCV for lettuce was recorded at Yarrowitch (\$19,000 ha^{-1} averaged across treatments), followed by Kirby in 2000 (\$17,000 ha^{-1}) and the lowest GCVs were observed in the trials at Laureldale (\$9400) and Kirby in 2001 (\$14,200 ha^{-1}) (Fig. 9A). Averaging the treatment responses across the trials, HD, HY and TI had the highest GCV, with values for CO slightly lower ($P = 0.014$), and considerably lower for PP.

The highest ACVs were recorded for TI, CO and HD, with an average for the three treatments in all trials of \$13,200 ha^{-1} (Figure 9B). HY had a mean ACV of \$8700 ha^{-1}, significantly lower than TI and CO ($P \leqslant 0.015$) but not HD ($P = 0.114$). PP had very low ACVs, with a mean loss of \$4100 ha^{-1} across trials. The ACVs showed a similar pattern amongst treatments at Yarrowitch and Kirby in 2001. The top four treatments in those trials, TI, HD, CO and HY, were similar. However different rankings were observed in the trials in 2000. At Laureldale, the ACVs for CO and TI were significantly higher than HD and

Table 2. Correlation (R^2) between weed variables for echinacea at harvest.

Variables	Yarrowitch 1999	Kirby 2001
Weed density–crop biomass	0.78 (0.91)[1]	0.34 (0.70)
Weed density–crop cover	0.90 (0.93)	0.51 (0.90)
Weed biomass–crop biomass	0.73 (0.80)	0.39 (0.67)
Weed biomass–crop cover	0.86 (0.87)	0.51 (0.78)
Weed cover–crop biomass	0.80 (0.88)	0.41 (0.76)
Weed cover–crop cover	0.98 (0.99)	0.57 (0.92)

[1] Values in brackets are the correlation when the PP treatment was excluded from the calculation.

HY, reflecting their lower costs. The response at Kirby in 2000 was unique amongst the trials with CO being the most cost effective treatment. TI and HD were equivalent to each other ($P = 0.493$) and HY was slightly lower ($P = 0.032$).

Discussion

The HD treatment was very effective for weed control in lettuce and echinacea and gave excellent crop yields. It is the most widely used method of weed control amongst organic herb and vegetable growers in the industrialized world[1,8] and amongst many farmers in the developing world[20], although it fails to draw much attention in several reviews of non-chemical weeding[21,22]. Hand weeding is usually considered expensive[7], although not always, especially in areas with cheaper labor costs[23]. The amount of time used in each application of the HD treatment (198–228 and 268–312 h ha^{-1} for lettuce and echinacea respectively) was within the range of reported times for various vegetable crops, which include 100–300 h ha^{-1} in organic carrots[24], 256 h ha^{-1} in echinacea[6] and up to 500 h ha^{-1} in organic onions[7]. One thorough hand weeding in lettuce was sufficient to prevent most weed growth up to harvest. While lettuce has several uncompetitive traits such as low growth habit, small root system and high nutrient and water requirements[25], the short growing season and the rapid early growth of the transplanted lettuce seedlings enable the crop to compete effectively against weeds and achieve good yields with a single weeding event[10,26]. Echinacea has a longer growing season, with limited growth in the first two months when the crop is very susceptible to weed competition[6]. Three weeding operations at 4, 8 and 12 WAP in the echinacea trials were required to maintain an adequate level of weed control up to harvest. Once shoot and leaf growth accelerate, echinacea becomes more competitive against weeds and can develop a dense, dominant canopy. The management emphasis should be on maintaining a high level of weed control up to about 10 WAP in echinacea.

Hay mulch gave good weed control and crop yields, although laying the mulch was time-consuming and some follow-up hand weeding was necessary. Hay and straw mulches have been successfully used for weed control and have generally produced good crop yields[4,23]. However, variable or negative responses have also been reported, commonly due to the prevailing weed populations, varying decomposition rates, the natural variability of the mulch and unevenness of laying[27,28]. These trials were generally free of aggressive rhizomatous weeds common in organic horticulture in Australia such as *Cynodon dactylon* L. (Pers.) and *Rumex* L. species[29], although annual weeds were able to germinate and emerge. Light penetration through the hay treatment is unlikely to have been

Table 3. Correlation (R^2) between weed variables for lettuce at harvest.

Variables	Yarrowitch 1999	Laureldale 2000	Kirby 2000	Kirby 2001
Weed density–crop biomass	0.38 (0.63)[1]	0.49	0.01	0.13 (0.53)
Weed density–crop cover	0.33 (0.69)	0.54	0.01	0.08 (0.44)
Weed biomass–crop biomass	0.30 (0.66)	0.46	0.01	0.09 (0.44)
Weed biomass–crop cover	0.17 (0.36)	0.07	0.02	0.10 (0.50)
Weed cover–crop biomass	0.11 (0.35)	0.16	0.03	0.08 (0.48)
Weed cover–crop cover	0.12 (0.40)	0.02	0.04	0.08 (0.44)

[1] Values in brackets are the correlation when the PP treatment was excluded from the calculation.

Table 4. The cost of weed control treatments (AU$ ha^{-1}) used in the echinacea and lettuce trials.

	Echinacea		Lettuce			
Treatment	Yarrowitch 1999	Kirby 2001	Yarrowitch 1999	Laureldale 2000	Kirby 2000	Kirby 2001
CO	0	0	0	0	0	0
HD	10,268	8,929	4,018	4,688	4,688	4,167
TI	4,164	3,798	1,165	890	890	994
HY	10,029	7,796	8,243	7,350	7,350	7,506
PP	12,864	13,088	12,418	Not used	Not used	11,785

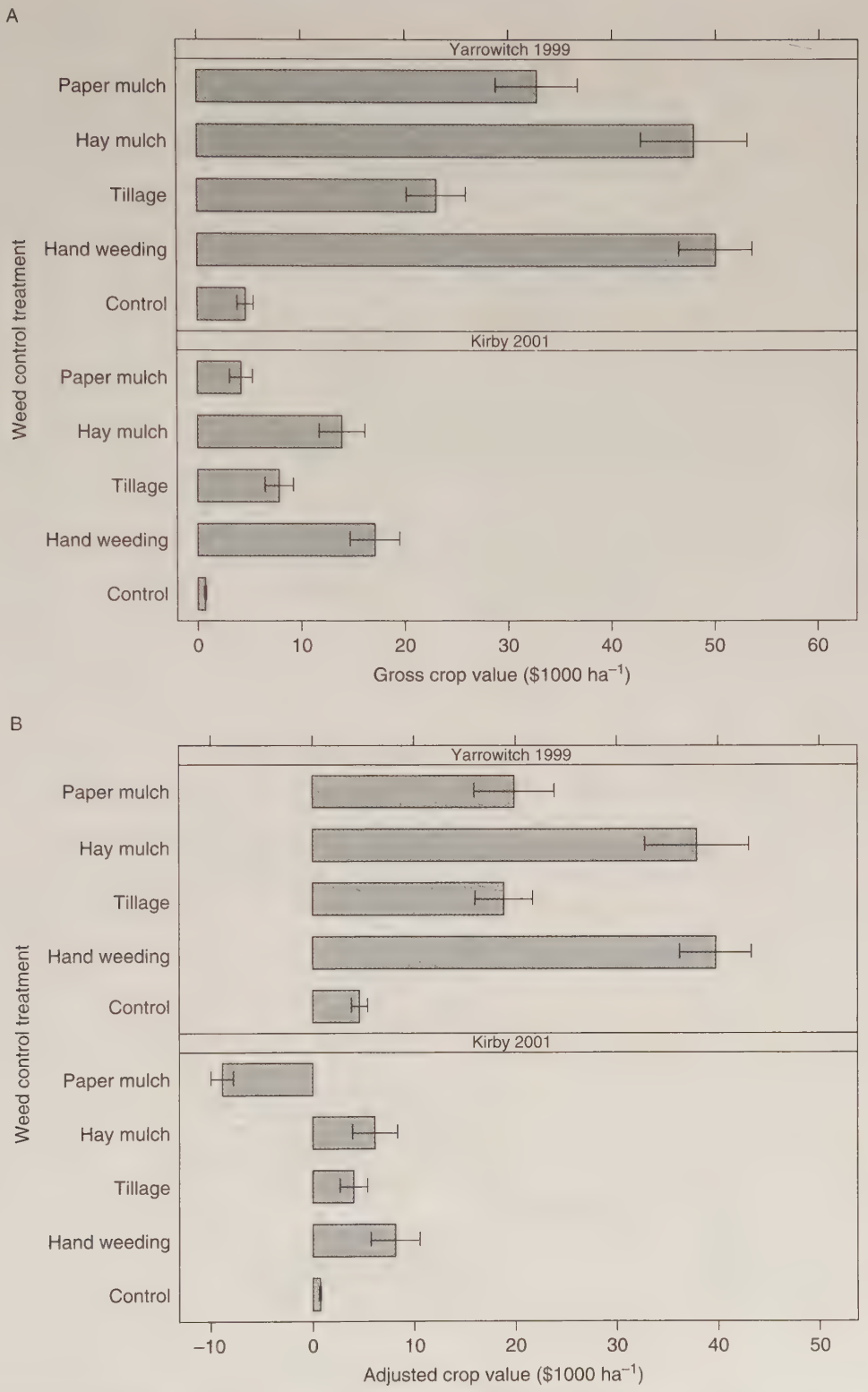

Figure 8. Mean and standard error of GCV (A) and ACV (B) of echinacea for the weed control treatments. Note different scales on horizontal axes.

completely prevented. Teasdale and Mohler[30] found that 8 and 16 tons ha^{-1} of ryegrass mulch (cf. 9.5 tons ha^{-1} for the HY treatment reported here) reduced incident light by 90 and 95% respectively, but that did not prevent germination in phytochrome-dependent weed seeds. Hay mulch was quite cost effective for echinacea, but was less economic for lettuce. The high labor input for laying mulch and supplementary hand weeding would only be justified in high-value crops and where the weed flora were suitable (e.g., rhizomatous weeds absent or few). In intensive

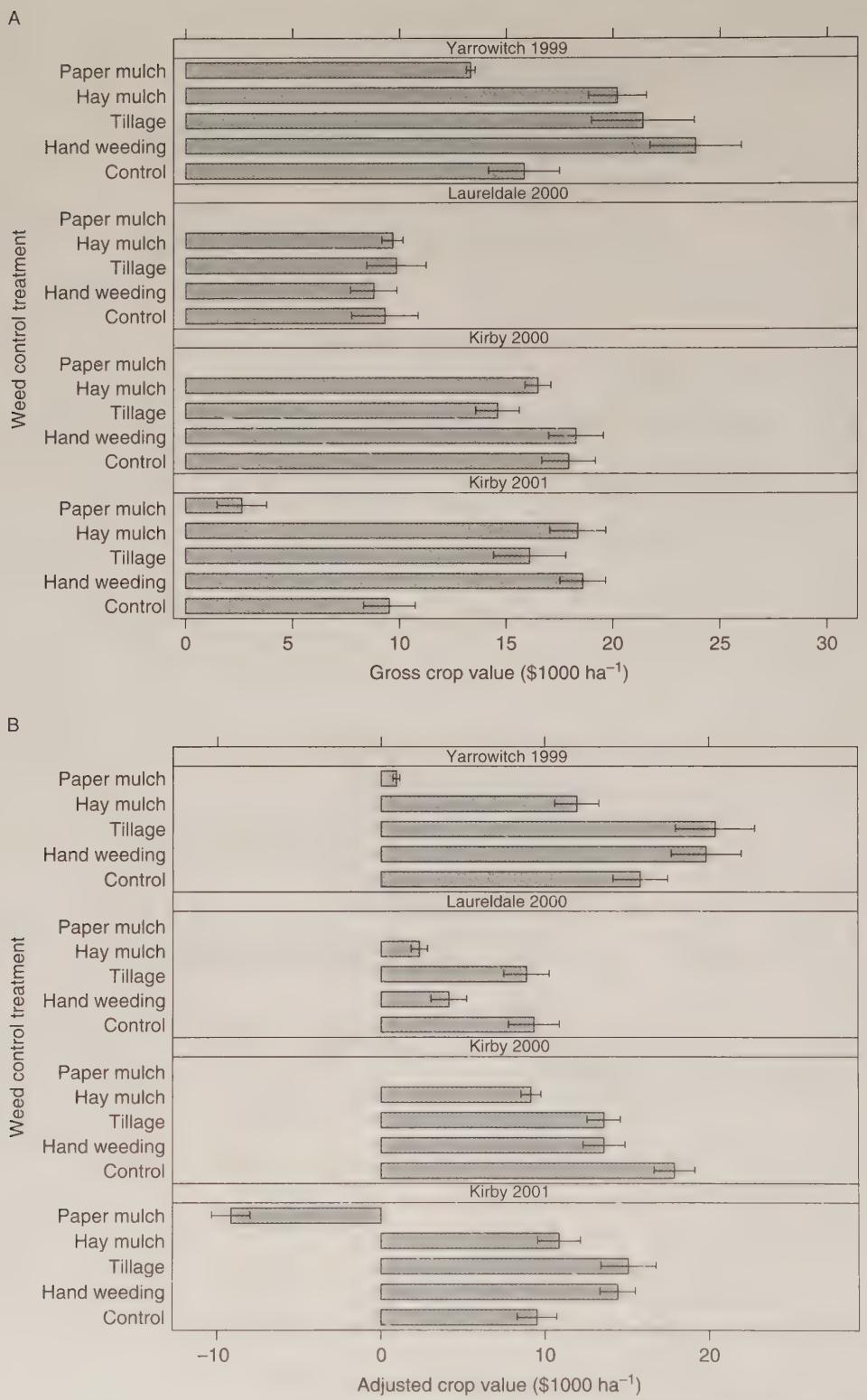

Figure 9. Mean and standard error of GCV (A) and ACV (B) of lettuce for the weed control treatments. Note different scales on horizontal axes.

organic production in Australia, heavy continuous mulching is often practiced. However, on larger farms where tractors are used to prepare the ground, permanent mulch cover is uncommon[8].

To overcome difficulties with laying bulky organic mulches, several options exist for mechanizing the management of mulches. These alternatives include roll-on mulches using existing plastic mulch technology[4], flowable

solids[31] and *in situ* cover crop mulches[32]. These methods are often expensive and require skilled management. PP was used in these trials as an alternative to hay mulches. While PP was more expensive to buy than hay, it was in a form that enabled quicker and more even application to the planting beds, and required less follow-up hand weeding. Several reports have noted better weed control by a newspaper mulch than mulches composed of crop residues[27,33]. A high level of weed control was achieved due to the thick, continuous layer that prevented light penetration for germination and weed emergence. In addition to surface area, the available space within a mulch is an important property[34]. The PP had very little space between particles compared with the hay mulch, especially after wetting.

Although the PP suppressed weeds effectively, crop yields were reduced, particularly lettuce. Lower yields under PP are commonly attributed to soil nitrogen immobilization in response to the high carbon:nitrogen ratio of the mulch[33,35]. A separate investigation found no evidence of phytotoxicity and leaf tissue nitrogen for lettuce was significantly lower[29]. The use of such a mulch is very limited unless the nutrient balance (C : N ratio) is addressed, for example by adding manure. The high purchase cost is also prohibitive in the current commercial environment. However, technical and policy developments such as improvements in feedstock (e.g., paper waste) availability and processing, and changes in recycling requirements by government authorities, may improve this situation[4].

Apart from the CO treatment, tillage was the least effective method of controlling weeds. Satisfactory weed control was usually achieved in the interrows but not in the crop rows where the competitive effects of weeds would be greatest. The treatment was more effective in sandier soils (e.g., Yarrowitch) where better weed displacement was achieved and in light weed loads (e.g., Kirby in 2000). The dominant weeds at all sites were mostly annuals that benefited from the transition from pasture to annual cropping due to their large numbers, precocity and fecundity, except *A. vulgaris* at Kirby. But *A. vulgaris* benefited from cultivation by the extensive redistribution of its root system and shoots along the planting beds. Individual tillage operations were not expensive, but the on-going costs accumulate over time, and extra hand weeding may be necessary. In a longer-season crop such as echinacea, repeated tillage operations were needed, reducing cost effectiveness compared with the other treatments. However, in a short-season crop like lettuce, a single tillage operation was sufficient, so tillage costs were very low. The implements used in the trials were basic chisel ploughs with limited ability to accurately control weeds close to the crop plants without damaging crop roots. While this type of implement is commonly used by organic herb and vegetable growers in Australia[8], more accurate, though more costly, implements are available[36]. Other research has also found that tillage can be less costly than hand weeding[7,37] and mulching[38,39].

The unweeded control treatment provided a measure of the pre-existing weed levels in each trial and a basis for evaluating the impact of the other treatments. In general, weeds were abundant in the control plots and crop yields were reduced, although lettuce showed potential as a quick cash crop without weeding when weed numbers were low. A study of radish (*Raphanus sativus* L.), a crop with a very short growing season, demonstrated that rapid crop development can avoid the need for weeding in short-season crops[40], particularly if the starting weed load is light. Relying on minimal control techniques that are effective in the short term may compromise the longer-term goal of weed seed bank depletion. The consequences of weed seed production by uncontrolled weeds on management in subsequent seasons would also need to be considered by growers, with a number of options available including grazing, mowing or tilling.

Differences in weed levels between trials were due to variations in soil conditions and bed preparation, weather and previous land use. The heavy clay soil at Laureldale caused the planting beds to have larger clods than in the finer structured soils at Yarrowitch and Kirby. Large soil clods can reduce weed seedling emergence and crop establishment. As expected, trials with greatest weed density and final weed biomass also had the highest rainfall. The six-fold increase in weed density observed at Kirby between 2000 and 2001 (previously uncultivated) parallels changes in weed levels at Yarrowitch after converting from grazing to annual cropping (P. Green, personal communication) and reported elsewhere[41,42].

There was no correlation between the cost of the treatments and the crop yield in these trials. A survey on weed management amongst Australian organic herb and vegetable growers found that the perceived expense of a weed control method was not related to the perceived success of that method[29]. Bond and Lennartsson[43] note that relatively expensive methods may be cost effective in certain cropping situations, and that success depends on matching the weed control technique with the cropping strategies. Several other factors influence the economics of weed management (and therefore the choice of methods) including the size of cropping area, prevailing weed density, the cost of labor and commodity price fluctuations[7,23]. The economic analysis reported here was specific to the time and location of the trials, and outcomes will vary depending on the availability of labor, machinery and implements, and suitable mulch materials.

Conclusions

Cheaper weed control methods such as tillage with limited follow-up hand weeding may be sufficient to ensure a reasonable yield for lettuce, a crop with a short growing season and rapid early growth from transplanted seedlings. The acceptable economic return of the CO treatment suggests that good weed control in the cropping area prior to planting may even be adequate. More expensive weeding

methods such as hand weeding and hay mulch are cost effective weed management options for longer-season and higher value crops like echinacea. Crop selection should be based on prevailing weed loads, as they will strongly influence the efficacy of the weeding methods chosen.

These trials indicate that hand weeding, tillage (even with unsophisticated implements) and crop residue mulches are cost effective in the appropriate setting. Integrating these methods (e.g. tillage and chipping), in association with other techniques such as strategic crop rotations, false seedbed preparation and fertilizer banding, may improve their effectiveness further.

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The adaptive consumer: shifting attitudes, behavior change and CSA membership renewal

Willow Saranna Russell* and Lydia Zepeda

University of Wisconsin-Madison, School of Human Ecology, 334 Human Ecology Building, 1300 Linden Dr., Madison, WI 53706, USA.
*Corresponding author: willowrussell@yahoo.com

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Abstract

A qualitative study was conducted with a subset of a Community Supported Agriculture (CSA) membership base in Wisconsin, USA to examine attitude and behavior change associated with membership. Changes that were examined included: modified eating or cooking habits, increased consideration of food seasonality and associated consumer preferences for seasonal products, and an enhanced appreciation for farming. Although this study investigated 'spillover' attitude or behavior changes (e.g. reduced driving or increased use of environmentally friendly cleaning products), none were observed. This study indicates that attitude and behavior changes are generated by the structural elements of CSA including exposure to the farm, interactions with the farmer, and the constraints imposed by a pre-selected bundle of vegetables. There was no indication that changes occur due to the development and enforcement of social norms within the CSA membership base. Community, in the context of this CSA, is expressed primarily as a conceptual community of interest. Our results suggest that demonstrated attitude and behavior change increases the likelihood that a consumer will renew their CSA membership.

Key words: CSA, community supported agriculture, behavior change, attitude change, consumer behavior, Troy Community Farm, CSA membership renewal, sustainable agriculture, local foods

Introduction

The Robyn Van En Center's 2006 database lists approximately 1700 Community Supported Agriculture (CSA) farms in the United States[1]. CSA members pay a farmer, or group of farmers, a lump sum of money at the beginning of a season in exchange for bundles of products (e.g. vegetables) at regular intervals. People join CSA for a variety of reasons including concern for the environment and sustainable food systems, desire for fresh and organic foods, and an interest in supporting local farmers[2–5].

For CSA farmers, economic viability is dependent, in part, upon their ability to attract and retain members. In the best case scenario, farmers will attract members that will return year after year, thereby reducing the amount of energy they have to invest in recruitment. This issue of retention was of particular concern to the managing farmer of Troy Community Farm, our study site, and our research was designed accordingly. In particular, this study explored the following questions. (1) Does demonstrated attitude and behavior change affect a member's willingness to renew their membership? (2) What are the ways in which people change their attitudes and behavior? (3) Are these changes generated by the development and enforcement of social norms within the membership base or are they generated by the structure of CSA (e.g. limited selection of products)?

CSA Membership and Attitude and Behavior Change

Lancaster established that consumers derive utility, not only from goods themselves, but from the 'intrinsic properties' of those goods that are often present in a 'bundle' of traits[6]. In the case of CSA membership this bundle of traits includes not only the quality (freshness and flavor) of the produce itself, but the interactions consumers have with the farm and CSA community and the sense of well-being or moral satisfaction that comes from supporting a system that consumers believe is good for the environment, their health and the health of their community.

Meeting these preferences alone does not guarantee that a farm will retain its members from season to season, however. Individuals who leave CSA generally attribute

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their decision to inconvenience and a lack of choice in the variety and quantity of produce items[2,4]. This gets to the heart of the issue: 'At a minimum CSA members must change habits of purchasing, processing, and eating to adapt to the production and distribution constraints of CSA farms'[2]. In this study it was therefore hypothesized that consumers who reported attitude and behavior change would be more likely to renew their membership.

Changing personal cooking and eating habits are some of the ways that members modify their behavior after joining CSA. However, O'Hara and Stagl showed that CSA members also adopt other preferences for supporting local farmers, buying organic foods and eating seasonally[7]. Some of these changes could be generated simply by the produce selection restrictions inherent to most CSA memberships, but it is also possible that other changes could occur due to exposure to the farm and interactions with farmers and other CSA members. O'Hara and Stagl stressed the importance of 'learning and institution forming' within CSA. Their research introduced the idea of 'endogenous preferences' or preferences that change over time within an economic institution or system. In the case of CSA, these changes develop during the course of an individual's membership[8].

The presence of endogenous preferences was explored in this study as opposed to *exogenous* preferences that might also have had an impact on changes in CSA member attitudes and behavior. Exogenous preferences are understood to 'change in response to "non-rational" factors such as advertising or other forms of "propaganda" ... and are assumed to be shaped by social and biological processes and institutional conditions outside the economic system itself'[8]. Hence, this study did not focus on factors such as social marketing aimed at 'greening' consumer behavior and buying local products or peer and family pressure consumers might experience outside the CSA membership to improve their eating habits. Instead this study focused on endogenous preferences that change *within* the CSA system in response to factors such as interactions between members or between members and the farmer and farm.

These concepts of endogenous preferences and institution forming fit well with the idea that human behavior is molded, in part, by social norms that are developed and enforced within communities[9]. Consumption patterns are similarly fashioned, signaling status, style and values within a social context[10,11]. At the onset of this study it was therefore conjectured that a CSA membership base could act as a behavior-shaping community, leading to greener consumer choices.

CSA, at face value, is a community effort. Members agree to share the risks of agriculture with the farmer. In effect, they sacrifice some control over individual well-being and choose to act within a group, a hallmark of community building[12]. DeLind and Ferguson cite this kind of collective activity as a mechanism through which members 'can build interpersonal trust and a sense of community rooted in place,' leading to enhanced commitment to sustainable choices[3].

The existence of community-generated behavior change could vary from farm to farm, however. O'Hara and Stagl stressed that members in a small, interactive CSA group are more likely to develop altruistic behavior (such as making sustainable choices) than those in a large, anonymous membership because the former provides 'moral muscle' that rewards certain behaviors and punishes others[7]. Other researchers have also questioned the definition of community within CSA. Cone and Myhre, for instance, found that the community aspect of CSA membership was ranked as a low priority for most members and that, on the whole, about half of the members they surveyed did not engage with the CSA other than to pick up their share[2]. They concluded that 'in reality "community" for a great many [members] referred more to a community of interest than to community built on mutual relationships of rights and obligations, on reciprocity'[2]. Agrawal and Gibson recognized that the 'concept of community as shared norms and common interests depends strongly upon the perceptions of its members; in this sense all communities are imagined communities'[12].

This study attempted to define the type of community Troy provides and establish whether social norms exist within that framework and whether they could contribute to modified behavior in the membership base.

Study Site: Troy Community Farm

There are approximately 24 CSA farms that serve over 1700 members in the greater Madison area of Wisconsin, USA. These farms vary in size, serving between 10 and 300 households[13]. Troy Community Farm is a medium-sized, organic farm on 2 ha of land that currently (as of 2006) serves 110 CSA members. Within this membership base approximately 10 spaces are available for worker share members that spend a total of 84 h on the farm in exchange for their share and 10 spaces for assisted memberships for low-income individuals and families. At US$400 a share, CSA provides about 55% of the farm's revenue (based on the 2005 income data) though the managing farmer hopes to increase this contribution over time. The remaining 45% is generated by retail sales at the farm and at two weekly farmers' markets (24%) and from wholesale revenues (21%). Current wholesale items include herbs, sprouts, and tomatoes. The farm employs a farm manager, farm assistant, interns from the University of Wisconsin-Madison, members of a high school farming program, and CSA worker share members.

Members of Troy Community Farm receive shares for 21 weeks from June to October. In addition to their share, members get *Urban Roots* (a weekly newsletter with recipes and farm updates), invitations to farm events, and are free to pick flowers and herbs from the farm at any time during the growing season. Members are involved with the farm at varying levels, starting with simply picking up their shares at the farm and extending to volunteering on the land

and participating in the Core Group. The Core Group works together to recruit new members, diversify the membership base ethnically and economically, locate and apply for grants, and so forth.

Troy Community Farm is unique in a few significant ways. It is one of the few urban CSA farms in the country, making it more accessible to city residents than other farms, but also limiting the amount and types of crops that can be grown in the restricted space. The farm also differs because it is part of a larger non-profit organization called the Friends of Troy Gardens (FTG). FTG currently oversees 10.5 ha of land. In addition to the farm, FTG manages community gardens, a high school student worker program called Farm and Field, adult education classes, a kids' garden, natural areas, a prairie restoration site, University of Wisconsin-Madison research projects, and is affiliated with a co-housing development that broke ground in March of 2006 on an adjacent 2 ha of land that are not managed by FTG (Fig. 1).

Methods and Data Analysis

This study was designed to be participatory in nature and the managing farmer of Troy Community Farm was consulted during research question design and throughout the preparation phase of the study. Her particular interest, as mentioned above, was how to retain members from season to season. Based on 2003–2006 membership data, Troy has a renewal rate of approximately 56% and they would like to bolster that number so that less energy has to be channeled into recruitment efforts each year. Troy is currently moving into its sixth year of operation at which time, according to Docter and Hildebrand[14], it should have a 75–80% renewal rate in order to be deemed 'successful'.

After the data had been gathered, analyzed and synthesized, the managing farmer had an opportunity to review and comment on the results along with a series of recommendations that were generated for the farm. She was not involved with the focus groups, however, so that participants would feel more comfortable expressing their opinions anonymously.

In this study four focus groups were facilitated with a total of 23 participants. Focus groups are semi-structured discussion sessions that engage a group of people on a certain topic or suite of topics. Results from focus groups are not meant to be representative of a given population due to the non-random and small-scale sampling techniques involved. Researchers organize groups according to common characteristics and can thereby compare them for a fuller understanding of the issue in question. These groups, if led well, encourage dialogue between participants that can reveal things that in-depth interviews or surveys would not[15].

Participants for the focus groups in this study were recruited by phone using CSA contact lists from 2003 to 2005 provided by the managing farmer. These lists were divided into four sub-groups according to shared characteristics. Groups 1 and 2 were comprised of current and returning CSA members. Group 3 included 'engaged members' that were either worker share members, participants in the Core Group, or both. Group 4 was made up of former members. Each person in every group was called at least once. For each group, calls were repeated until a focus group of 9–12 individuals was formed. Focus groups typically range in size from six to 12 individuals and in the recruitment efforts of this study the target was set slightly higher in order to accommodate for attrition[15]. Reminder calls and emails were placed and sent out the day before the session to help limit this loss of participants. However, in Groups 1, 2, and 4 there was an average attrition rate of 27%. The final composition of the focus groups was therefore based on successful contact, willingness and availability.

The focus group sessions ran for approximately one and a half to three hours and included time to eat, settle in, and fill out a pre-meeting survey to capture demographic and basic supportive information. (After the first focus group met, some slight changes were made to the pre-survey for clarification. The changes to this survey are noted in Appendix 1.)

Focus group discussions were facilitated in a semi-structured way, instituting a 'round-robin' technique that offered everyone an opportunity to speak, while providing for deviations if a discussion style conversation started or if individuals wanted to add something out of turn. The order and delivery of the questions varied at times to accommodate conversation flow and improve clarity, but did not deviate significantly from the standard list (Appendix 2) with the exception of Group 3's discussion. This group was particularly engaged and talkative and, in the interest of time, questions 1 and 3 of Part II were skipped. These questions were addressed during the rest of the session coincidentally. In Group 3 there were also two group members that had to leave an hour early, so their input was not collected for a portion of the session.

All of the focus group sessions were audio recorded and transcribed. Transcripts were used to identify themes, which were coded for commonalities and collapsed into broader thematic groups. Frequencies with which these broad themes occurred within individual groups, and among all the participants as a whole, were then determined. (Frequencies were defined by how many individuals mentioned the theme, not by how many times it was mentioned by the same individual.) For supplementation, the frequency of topics brought up in the focus groups was compared with quantitative measurements from the 2004 and 2005 end-of-season surveys, which were previously carried out by Marcia Caton Campbell and Troy Community Farm. The response rates for these surveys were 25% (15 out of 60 members) and 44% (35 out of 80 members) respectively.

As with all case studies, generalizability is very limited as these results pertain specifically to Troy Community Farm, which, as mentioned above, is unique in a number of ways that might affect the types of members it attracts. For

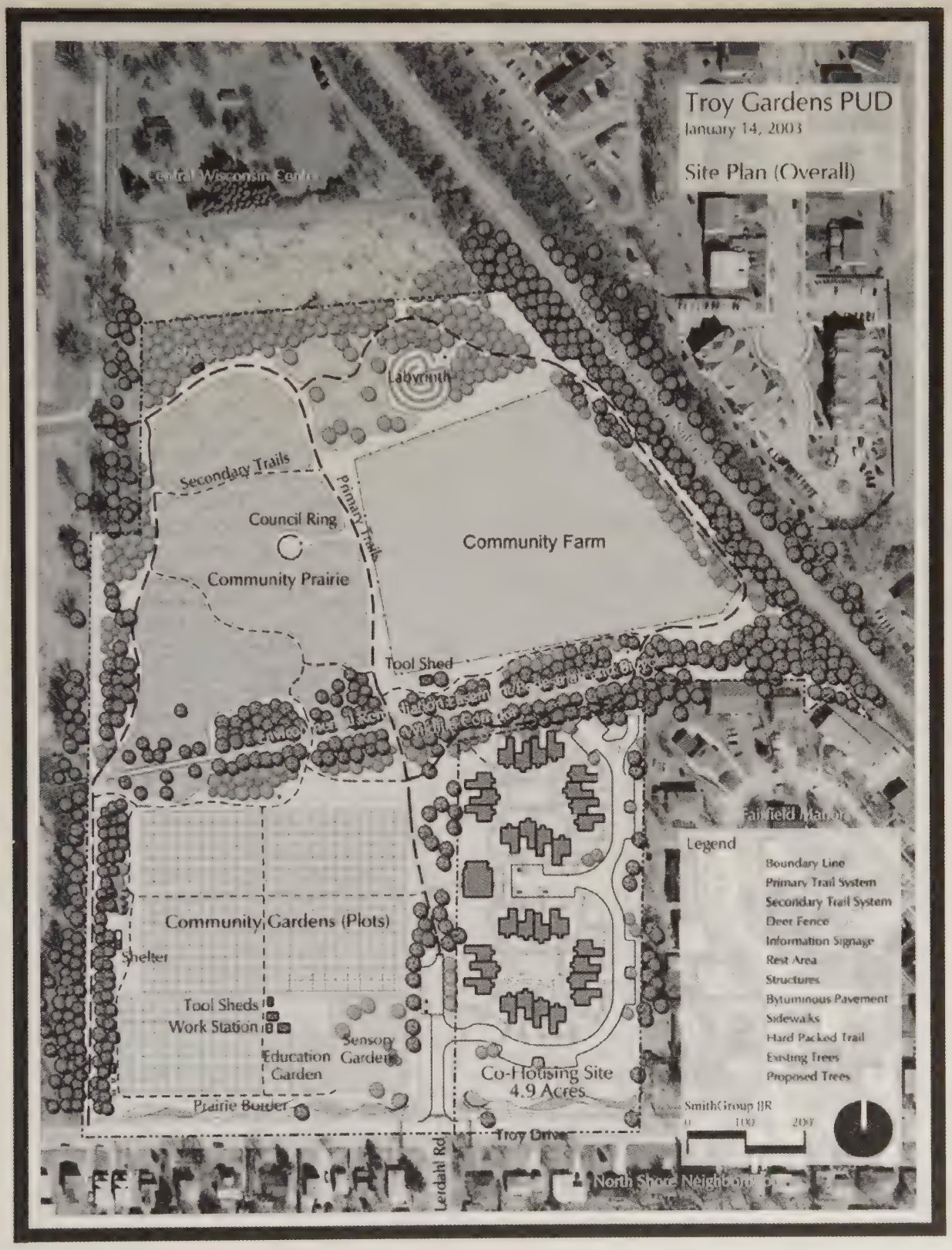

Figure 1. Map of Troy Gardens of which two hectares is dedicated to Troy Community Farm (see online for a colour version of this figure). Source: FTG Web site: http://www.troygardens.org/pictures/sitemap.jpg

instance, Troy is an urban farm and thus quite attractive to neighborhood residents. It is also part of a larger non-profit organization that manages community gardens, natural areas, and educational programs that provide added value for some members. Additionally, results from these focus groups may not be representative of the Troy CSA

population as a whole since only 18 current members (plus five former members) participated in the focus groups, constituting 23% of the 80 consumers that were members in 2005. Results are also subject to sample selection bias as the type of people who participated might have very different views from those who did not.

This study examined behavior change through retrospective reporting, which might not yield results that are as reliable as in an experimental design that tested behavior before and after the participants' exposure to CSA. The data were also dependent upon self-reporting, a particular problem when investigating behavior that relates to values and perceptions of an appropriate code of conduct. Furthermore, it is difficult to identify whether CSA membership is a driver for attitude and behavior modification or if the values that lead to becoming a CSA member also drive the other changes. Despite these limitations, however, this study does provide interesting exploratory results and a foundation for further research.

Demographic Background of Participants

The pre-survey revealed that the CSA members in this study are fairly representative of the age distribution (not including individuals under 20) and marital status (partners are considered single in the US Census) in the US population (Table 1)[16]. However, they are a little older and less likely to be single than the average resident of Madison, Wisconsin (which has a large university student population). They are also more educated than the average US citizen and Madison resident and are more likely to be female. The gender bias may be attributed to the fact that, in the average household, women often make the grocery shopping decisions. When surveying household shoppers in the United States, Zepeda and Li discovered that 65% of their respondents were female[17].

Participants in this study tend to be Caucasian (note that African Americans, who make up 12% of the US, and 7% of the Madison, population, are not represented at all), which is not entirely consistent with the US population, but is fairly representative of Madison's ethnic distribution. These CSA members are also less likely to have children living at home and are a little more likely to be employed than the average US or Madison citizen. Their income distribution is fairly similar to that of the US and Madison populations in the upper income brackets (above $60,000). However, there were proportionately more participants with incomes between $30,000 and $60,000 than those with incomes below $30,000 when compared to the general population. These demographic results are fairly typical of CSA members[2,3,5].

Changes in Attitude and Behavior among Renewing CSA Members

Almost all of the renewing CSA members in this study experienced some sort of attitude or behavior change since they first joined CSA. Such changes were not found among non-renewing members (discussed in detail below). The most common shifts (occurring in all of the current member focus groups) included alterations in food preparation and increased consideration of food seasonality, which sometimes resulted in different consumer choices. Other common trends included changes in diet and increased appreciation for farming. These changes were directly related to food or farming and did not appear to spill over into other areas of consumption such as driving habits or use of biodegradable soaps.

Increased awareness of seasonality and appreciation for farming

Seasonality became an important factor for two-thirds of the current CSA members. For many this has translated into an attitudinal shift: 'I think it's good for everybody. I think, especially in America, you just get used to [expecting that] whatever you want is going to be there. If you've got the money to buy it, you'll get it. I think it's good to remember that there are forces beyond that, and that nature is one of them'. For some participants these changes in attitude were expressed in different purchasing decisions: '... now we're a little more persnickety about [seasonality] and we'll kind of ask ourselves the question, "do we really need the red pepper from Israel right now?" Or, "can we really afford these?"' For some members, CSA prompted or empowered them to act on pre-existing knowledge and values: 'I think part of it is learning to eat what is in season, and the farm share really helps that because you don't want to waste it, so you start looking for recipes that are relative to whatever is in the farm share. Even though ... I thought that was a cool idea before I got the farm share, the farm share sort of pushed me to [act on it]'.

These participants buy seasonally for various reasons such as the social and environmental implications of importing foods from around the globe. They also noted the reduced quality and high price of off-season produce: 'I think that over the winter I became a lot less tolerant of grocery store produce. I would just rather not eat lettuce if it's not going to be good'. However, for a smaller percentage of the participants, their enhanced awareness has not prompted seasonal consumer choices: 'It hasn't really changed my behavior any, but when I do go to the store, sometimes I think about where [the produce] is ... in the cycle and also what types of vegetables grow in this area, as opposed to other areas'.

In addition to increased consideration of seasonality, over half of the renewing members in this study discovered that they had a new level of understanding and appreciation for farming: 'I think I've come to understand a little bit better the difficulties of being a farmer ... And just appreciating ... the hardships that [they] go through'. For some members this has changed their attitude about food availability: 'I remember Claire writing in the newsletter of how she was very disappointed in some of

Table 1. Participants' demographic information as compared to US and Madison, Wisconsin population demographics (n = 23)[16].

Demographic	Raw #	% of participants	% of Madison pop.	% of US pop.
Age[1]				
Range	22–85			
Mean	47			
20–29	4	17%	33%	19%
30–39	5	22%	20%	22%
40–49	5	22%	18%	21%
50–59	4	17%	13%	15%
60–69	3	13%	7%	10%
70–79	1	4%	6%	8%
80+	1	4%	3%	5%
Sex				
Female	17	74%	51%	51%
Male	6	26%	49%	49%
Education				
High school	1	4%	18%	29%
Associates	2	9%	8%	6%
Bachelors	12	52%	27%	16%
Masters	4	17%	13%	6%
Professional	1	4%	4%	2%
PhD	3	13%	4%	1%
Ethnicity				
Caucasian	20	87%	86%	77%
Asian American	1	4%	7%	4%
Undisclosed	2	9%	NA	NA
Marital status				
Single	7	30%	57%	46%
Married	12	52%	43%	54%
Partner	3	13%	NA	NA
Undisclosed	1	4%	NA	NA
Dependents in home				
Yes	4	17%	48%	68%
No.	17	74%	52%	32%
Undisclosed	2	9%	NA	NA
Employment				
Employed	20	87%	73%	64%
Stay at home parent	1	4%	NA	NA
Retired	2	9%	NA	NA
Annual household income				
Less than $30,000	3	13%	34%	35%
$30,000–$59,999	13	57%	34%	32%
$60,000–$89,999	3	13%	21%[2]	13%[2]
Over $90,000	3	13%	11%[3]	12%[3]
Undisclosed	1	4%	NA	NA
Primary food shopper				
Yes	14	61%	NA	NA
No	0	0%	NA	NA
Shared	9	39%	NA	NA

[1] Census age percentages exclude individuals under 20 (29% of total population) as they are unlikely to be paying CSA members.
[2] Approximate comparison: Census income brackets did not match brackets used in this study: $60,000–99,999.
[3] Approximate comparison: Census income brackets did not match brackets used in this study: $100,000+.

the earlier stages when things were really hot, and dry, and the CSA shares weren't as big as they hoped they would be. We just kind of empathized with that ... If I go to the grocery store, and there's no red peppers there, I say, "damn it, where are my red peppers?!" ... The weather is important to me now. It's not like I just want it to be

Table 2. Frequencies of topics mentioned pertaining to attitude and behavior change among CSA members (expressed as a percentage of possible occurrences).

Types of behavior change	Total focus group ($n = 23$)	G1: current members ($n = 5$)	G2: current members ($n = 5$)	G3: engaged members ($n = 8$)	G4: former members ($n = 5$)
Changes in food preparation	61%	100%	80%	63%	0%
Consider food seasonality when making purchasing decisions	52%	60%	100%	50%	0%
Eat healthier/Eat more fresh vegetables	43%	80%	80%	25%	0%
Gained appreciation for farming	43%	20%	100%	50%	0%
Store more vegetables	26%	40%	40%	25%	0%
Waste less food	22%	60%	40%	0%	0%
Buy more organic foods and products	22%	40%	60%	0%	0%

Notable differences are indicated in the shaded box.

75 degrees and sunny. I want there to be rain so that Claire has a good season'.

Altered food preparation and shifting diets

Renewing members' food preparation habits changed in various ways. Some began to plan their meals more carefully and around the produce that was available in their share, adapting and, in most cases, enjoying the challenge that a limited selection of produce posed for them: 'I feel way better, knowing what I'm going to eat ... I love to cook. I just feel like it's so much better now ...'. Many changed how and what they cooked, trying new techniques and becoming more involved with their food preparation: 'I think it causes me to cook from scratch a lot more'. Some participants tried new foods: 'I find because of the recipes [in the newsletter], I have some ingredients in my cupboard that I never had before. Balsamic vinegar and tamari, some of those things. So the vegetables I make tend to be a little more interesting ...'. Another participant learned that '[t]here's so much out there besides what Copps' produce section had. I had no idea. It really opened my eyes to the world of vegetables'.

Other participants found that they are encouraged to eat out less and at least one member thinks more about where he dines out: 'I think: "do they buy food from our farmers or from another farmer around here". So that sort of becomes like another decision-making factor when we go out to eat'. About one-fourth of the current members find that they freeze or store more vegetables and produce less waste. These data are complemented by the 2004 and 2005 member survey results in which an average of 84% of the respondents indicated that their cooking knowledge has increased since joining CSA.

These surveys also show that 86% of the respondents are eating more vegetables and 89% are improving their nutritional health since they joined Troy CSA. Members in the focus groups found that they now eat more fresh vegetables and often associated that with the development of healthier eating habits: 'I think every year we get a little bit healthier ... We try new things, and we're more creative, and we're more adventuresome. I think that carries through. [CSA] does feed your habits, for our family, even after the crops'. Another member found that '[d]uring the year I was definitely eating more vegetables, and vegetables I've never eaten before. That is what is kind of cool about ... getting one of these [pre-selected shares]. If I was at the farmer's market, I wouldn't have purchased it for myself'. Those members raising families feel that CSA has benefited their children as well: ' ... my kids are so aware of vegetables, and being organic, and things ... When they have a choice of different foods, they'll pick healthier foods. I think that [CSA] was a really good education'.

For a few members focusing on fresh vegetables has moved them away from eating meat: ' ... especially since joining the CSA, I've been trying to base a lot more of my meals around vegetables, and try to put some type of vegetables in my meals. Growing up, my mom was very meat, potato, vegetable type of meals. This is a radical shift for me, and it's very welcome'. One member revealed that '[w]e eat a lot healthier since we joined CSA. We are edging further and further towards becoming total vegetarians'. In some cases these changes also influence other family members.

A small but adamant percentage of the participants also indicated that they buy more organic foods and products now that they are a part of CSA: ' ... we've just totally kind of gone organic—milk and everything ... It was a gradual change with being involved with the CSA'.

Notable differences between groups

The most notable difference between the four focus groups (Table 2) was demonstrated by the absence of attitude and behavior change in Group 4 (former members). This phenomenon is discussed in the context of willingness to renew later in this paper. In addition to this, changes in Group 3's eating habits (i.e. adopting a healthier diet, eating more fresh, organic vegetables) were less pronounced than in Groups 1 and 2, with the exception of trying new foods.

Instead this group emphasized changes in their appreciation for farming and consideration of seasonal produce.

There are a few possible explanations for this: (1) this group has a greater interest in the broad social and community benefits of CSA, which is likely as this group has committed more time and energy to the cause, (2) the members in this group have already made the dietary shifts mentioned by the other two groups, and specifically sought out CSA as a way to satisfy those preferences, which was specifically indicated by a few of these members, and/or (3) they have a greater interest in farming as an activity than the produce they acquire as a result of their labor.

Factors Contributing to Attitude and Behavior Change

Limited social interaction

This study indicates that the renewing members have a strong commitment to, and affinity for, the managing farmer. However, there is very little actualized interaction among CSA members. It is therefore unlikely that any of these shifts in attitude and behavior are influenced by community-driven social norms within CSA.

When this study was conducted almost all the members retrieved their shares from a stand set up at the farm itself on Thursdays between four and six-thirty in the afternoon. The exception to this would only occur if a member was not able to pick-up their share in the assigned time period. In these instances members would retrieve the share from the managing farmer's front porch later that night, but the norm was to visit the farm itself.

During CSA share retrieval, members had the opportunity to interact with the farmer, assistant farmer, volunteers, high school students working at the farm, and other CSA members. They also had the option of taking a three-minute walk from the farm stand to the farm itself and pick herbs and flowers. In such a scenario, one would expect there to be some interaction between the members, particularly in comparison to CSAs that deliver shares to individual homes or to another off-site location. However, when prompted to share a social experience they had with another CSA member the majority of participants in all the focus groups (except the engaged member group) had no stories to tell. The managing farmer said that she has observed the members talking to each other at the stand when they pick up their share, but only six participants mentioned this themselves and the focus group discussions indicated that social interactions rarely extended beyond this polite chitchat. Non-CSA-related interactions were almost never mentioned in all the groups except Group 3 (engaged members) and even in that group these instances were limited to the occasional informal conversation when members would bump into each other at the local cooperative grocery store or farmers' market.

Among working share members there was a little more interaction. However, one member expressed that these conversations are 'not very serious' and another mentioned that the socializing while working varies tremendously from week to week, and 'there are weeks where there's just something really fun that happens, just the type of conversation bantering back and forth, and then there's these kind of surly weeks when everyone is doing their thing.' There was also one participant that said there was never any time to talk while working.

The low occurrence of social interaction among CSA members could be explained in a few different ways. It could be attributed to the fact that members already have their own established communities and are not interested in building new relationships or getting involved with additional projects. They may have limited time and therefore do not engage in civic or broad social activities and perhaps CSA provides a convenient and simple way to connect to the land and community. It is also possible that members are more interested in developing a relationship with the farmer than other members. The data in this study certainly suggest that the members value their interactions with the managing farmer, which is consistent with the work of Bregendahl and Flora[7]. In their study they discovered 'that CSA members may value their relationship with producers more than they value their relationship to other members'[7]. In the year following this study Troy Community Farm started using one off-site location for CSA delivery at a local cooperative grocery store. It would be interesting to compare the retention rate of these members, who do not have weekly interactions with the farm and farmer, with those that do.

A conceptual community of interests

Despite the low level of interaction among members, a common trend in Groups 1, 2, and 3 was an affinity for the sense of community that CSA provides. It seems that Troy CSA members glean utility from a conceptual community of interests, rather than a community based on an actualized network of relationships, social norms and reciprocity, which is consistent with Cone and Myhre's work[2].

The majority of the participants in this study believed that they shared common interests and values with the other CSA members. They recognized that this was primarily an assumption, since they had such limited interaction with other members, but they still sensed that this was a group of like-minded individuals: ' ... if I were to talk to some CSA member out of the blue, I'm pretty sure I'd find plenty in common with them'. In Group 1 this inquiry about common interests led to a participant initiated discussion about how many CSA members would shop at Wal-Mart. A quick poll around the table indicated that a defining quality of CSA members in this group was the conceptual, and in most cases, actualized, rejection of this establishment.

A number of members spoke of this community of interest as a favorable aspect of their membership: 'It is also a little bit of sense of community, just belonging to the group, seeing the same people each week, picking up your

vegetables, and realizing that in some way we share the same values, I think, is real nice'.

The former members were less comfortable claiming common interest with the other CSA members: 'I don't really know ... We all paid to get a box. We all have the same principles. We believe in the CSA. We believe in fresh and organic, but without actually knowing anybody ...'.

Structure of CSA

In the absence of an actualized community it appears that attitude and behavior change are linked to the structure of CSA rather than social interactions. This structure (1) forces members to make dietary and related behavior changes by restricting their choice, (2) educates and exposes them to different foods and preparation techniques through pre-selected produce and recipes provided in the weekly newsletter, and (3) introduces them to the seasonality of foods and the benefits of eating accordingly. These adaptations might be amplified by members' predisposition, or even desire, to change their behavior, which might have brought them to CSA in the first place.

This complements O'Hara and Stagl's endogenous preference argument and their results, which show that member preferences for organic produce, supporting a local farmer, seasonal food consumption and knowledge of food origin were enhanced over time. It is possible that social norms could develop in smaller, active sub-groups within Troy CSA (like the Core Group) if facilitation and organization was increased within the membership base and the farm, providing the forum to cultivate relationships and 'moral muscle' that shape and enforce social norms[7].

How Attitude and Behavior Change Relate to Willingness to Renew

Limited choice, attitude and behavior change, and renewing members

Generally, this study indicates that members stay with Troy because they want to (1) access high-quality (and, to a lesser extent, organic) produce, (2) support local farmers, (3) get exposed to new foods by receiving a pre-selected bundle of vegetables, and/or (4) be a part of community. Troy Community Farm in particular attracts and retains members because it is (1) an urban farm in close proximity to its members, (2) a part of a larger organization (FTG), and/or (3) because there is sense of loyalty to the managing farmer.

Overall, these results are fairly consistent with the current literature, except for the emphasis on exposure to new foods, the added value of pre-selected produce, and the positive attitude and behavior changes associated with those elements. Most of the CSA literature attributes attrition to consumers wanting more convenience and choice, but many of the participants (Groups 1–3) in this study indicated that they preferred the *lack* of choice that CSA provides. For instance one CSA member said: 'I like having to work within certain parameters of choices because it makes me try things that I might not try otherwise ... It's sort of a hoot to see what I can do with it'.

Members not only enjoyed the challenge and introduction of new vegetables, they also relished the surprise and inspiration generated by their weekly bundle: 'One of the things I liked best about it is the surprise. What are you going to get next week? Saying, okay, I can try some new recipes'. Another member relayed that when you pick your share '[i]t inspires you. You don't get that from the grocery stores'. A few of the members adapted to the CSA lifestyle by planning menus around their weekly produce and found the additional structure to be beneficial. They wasted less food, adopted a healthier diet, and in a couple of cases, saved money.

Limited choice, attitude and behavior change, and non-renewing members

Non-renewing members in this study tended to (1) have a strong preference for self-selected vegetables, (2) not feel like they were a part of the community, (3) perceive that they are not being treated fairly, and/or (4) leave for personal reasons.

Among these reasons the most common element was a preference for self-selected produce. Four out of five of the former members indicated that they preferred their current situation of self-selecting their produce by shopping or growing their own, to the restricted selection of CSA. This strong preference could explain the lack of behavior change experienced by this group. Perhaps, willingness, or even desire, to change is part of what defines a returning CSA member. Additionally, the lack of attitudinal change with regard to the hardships of farming probably caused these members to be less forgiving when the produce did not meet their expectations. In turn, the absence of attitudinal change is probably related to this group's general disappointment with the community aspect of Troy CSA.

As a result of these findings the managing farmer has made a commitment to resolve some of the information and community building issues that disappointed these former members. However, it is possible that with their primary preference for self-selection, these individuals would still not maintain their membership. In fact, some of these former members still buy produce from Troy Community Farm; they simply do it at the farmers' market where they can purchase what they like and leave the rest.

These results prompt practical questions within CSA. Should CSA farms restructure their services to provide more selection for their members? Or, conversely, should they invest in educating their members on the benefits of various foods, the merits of menu planning around

a pre-selected bundle of produce, and the ways in which they can use unfamiliar items?

This study does not provide a definitive answer to these questions and, even with further research, it may be difficult to determine a 'one size fits all' solution as CSA farms vary significantly in size, location, philosophy and so forth. However, this study implies that a combined revenue stream that includes CSA memberships and retail sales, such as at a farmers' market or at the CSA farm stand, might provide a way to attract different kinds of consumers. It also implies that making small investments in broadening selection opportunities and education could be beneficial. For instance, Troy provides recipes in the CSA newsletter and allows members to pack their own shares and leave items that they dislike.

While this study does not point to a single optimal structure, it does have implications regarding whom to target when looking for CSA members that will renew. Strategically recruiting consumers who are desirous of positive changes in their diet and cooking habits could reduce the need to restructure CSA *or* invest a great deal in educating members. As this study illustrates, some members find utility in the current structure of CSA, making pre-selected produce a marketable feature. Conversely, members who have a strong preference for self-selected produce are unlikely to change, particularly if they have access to a farmers' market or the opportunity and ability to grow their own produce. Therefore, utilizing the CSA structure to inform recruitment strategies and to identify successful members might prove more beneficial than restructuring CSA or educating members.

Concluding Thoughts

This study indicates that members who are willing (or even seeking) to change their behavior, and in fact gain utility from the altered lifestyle, are more likely to renew their CSA membership. It also suggests that behavior change in members extends beyond simply modifying eating and cooking habits and includes altered consumption patterns with regard to produce seasonality and attitudinal shifts that demonstrate an increased appreciation for farming, which could also contribute to membership renewal. Changes were limited, however, to food- or farm-related attitudes and behaviors and did not spill over into non-food consumption categories.

Demonstrated changes are most clearly associated with the structural elements of CSA (i.e. exposure to the farm, interaction with the farmer, pre-selected produce, etc.). They do not seem to be connected to the establishment and enforcement of social norms by the members themselves. Though members clearly indicate that they value their relationship with the farmer, the CSA member community is conceptual and is not a system where relationships and reciprocity could govern behavior.

For CSA farmers these results imply that marketing to a population poised for behavior change could be beneficial (e.g. people who want to improve their diet, incorporate more whole foods into their cooking, etc.). This market could be reached through human health outreach centers, weight loss support groups, and associated publications. Insurance companies also offer another potential pathway, particularly if CSA farms can depend on financial support and advertising from these companies. For instance, Physicians Plus, a Madison-based HMO, now offers a US$100 rebate for individuals and a US$200 rebate for families who join a CSA and has produced a marketing campaign to promote this program. The decision on the part of Physicians Plus seems justified as our research shows that many Troy members have improved their nutritional health since joining CSA, making this a win–win situation.

Although the behavior change illustrated in this study does not seem to be spilling over into non-food-related consumer decisions, it still implies that there are indirect social and environmental benefits associated with CSA membership that extend beyond the direct effects of buying local, organic produce. Healthier eating habits, increased vegetable consumption, and decreased meat consumption produce healthier citizens and reduce the medical costs affiliated with obesity and other diet-related diseases[18–21]. Decreased meat consumption is also better for the environment, as a vegetarian diet has a much lighter ecological footprint than its omnivorous counterpart[22]. Additionally, increased consideration of produce seasonality can affect other food purchases beyond the CSA bundle. These increasingly local and seasonal diets reduce the environmental impact of transporting food across the country (and the globe) and support a diversity in agriculture that is more resistant to disease and catastrophe[23].

It should be noted again that this case study is limited in its generalizability due to the small sample size and the uniqueness of Troy Community Farm. The use of retrospective self-reporting on behalf of the participants is also a limiting factor when investigating behavior change. However, as an exploratory study it provides fertile grounds for further research. In the future it would be interesting to compare a selection of CSA memberships in a longitudinal study (including before and after investigations) to see how behavior change is expressed under varied circumstances over time. Within that research it would also be advantageous to rigorously examine non-food-related behavior change and explore the ways in which these separate CSA memberships define community in order to further flesh out how social contexts affect behavior.

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Appendix 1

*Troy Community Farm CSA Focus Group: Pre-Survey (Version 2) [Questions that were changed or added are noted with an *]*

Thank you for volunteering to participate in this CSA focus group. Please take a few minutes to fill out the following information. This pre-survey will help inform the results of our study. Although we ask for your name, it will only be used for our own tracking purposes. Your name will not be associated with any of the results included in the final study.

General Information:

1. Name:_____
2. Age:_____
3. Marital Status (please select one):

   ____Single ____Married ____Partner (living together, but not married)
4. *Do you have dependent children living with you in your home?

   ____Yes ____No

   If yes, what is/are their age(s):_____
5. Education: Highest degree obtained (please select one):

   ____High School ____Bachelor ____Masters ____PhD ____Other:
6. *Occupation and Employer:_____
7. Approximate annual income (please select one):

   ____Less than $30,000 ____$30,000-$59,999 ____$60,000-$89,999 ____More than $90,000
8. Ethnic Background:_____
9. Are you the primary food shopper in your household (please select one)?

   _____Yes ____No ____Food shopping is shared

Troy Related Information:

10. Did you know that Troy Community Farm is part of a non-profit organization called the Friends of Troy Gardens?

    ____Yes _____No
11. Did you know that the Friends of Troy Gardens:

    a. Has a prairie restoration area?

       ____Yes ____No

    b. Runs a kids' garden?

       ____Yes ____No

    c. Runs a youth program called Farm and Field with high school students?

       ____Yes ____No

    d. Provides space for community gardens?

       ____Yes ____No

    e. Is part of a larger project to build affordable co-housing in the land adjacent to the gardens?

       ____Yes ____No

12. During the most recent year that you were a Troy CSA member how often did you read Urban Roots (the CSA newsletter)?

_____Every time ____Once in a while ____Never – I don't have time ____Never – not interested

13. Reasons you first joined Troy Community Farm (please rank your top 5 reasons on a scale of 1-5):

____I like getting farm fresh vegetables
____*I like getting organic vegetables
____For health reasons
____For my children
____*For the quality of the produce
____*I believe that buying locally reduces the energy costs of importing vegetables
____*I believe that organic growing practices are better for the environment
____I feel good about sharing in the benefits and risks with those who grow the food
____I like being able to choose my own specific vegetables from the pick-up table
____*I like getting a pre-selected bunch of produce
____I like that the farm is right in the city
____I like that the farm is in my neighborhood
____I like supporting local businesses
____I like picking my own flowers and herbs from the CSA garden
____I like seeing and talking with the farmer and the folks who grow my food at the pick up site
____*I like seeing and talking with other CSA members

Other(s): _____

Appendix 2

Focus Group Questions

Each group was presented with the following questions (there was some variation in order and structure to facilitate individual discussion flow):

Part I

1. Initially, why did you join CSA in general?
2. Initially, why did you join Troy specifically? What was different or unique about Troy?
3. Why did you decide to renew/give up/change you membership? Did your perception of Troy change after you decided to join?
4. What could be done to improve Troy Community Farm?
5. In what ways did you engage with the farm and gardens (e.g. did you pick up your produce at the farm, attend an event, work on the farm)?
6. How far do you travel to pick up you share? By what means? Are you happy with this situation?
7. How much additional shopping do/did you need to do? Where (else) do you buy vegetables?

Part II

1. Can you describe a positive and/or negative experience you have had with the farm?
2. Do you know or socialize with any of the other CSA members? If so, in what ways? What do you talk about? Did you know them before joining Troy?
3. Can you describe a positive and/or negative experience you have had with other CSA members?
4. What do you have in common with the other CSA members besides Troy?
5. What have you learned since joining Troy CSA? From who? How has this affected your behavior?
6. Has your lifestyle or have your habits changed since you joined Troy CSA?

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Soil nutrient and plant responses to solarization in an agroecosystem utilizing an organic nutrient source

R. Seman-Varner[1,*], R. McSorley[1], and R.N. Gallaher[2]

[1]Department of Entomology and Nematology, University of Florida, PO Box 110620, Gainesville, FL 32611-0620, USA.
[2]Department of Agronomy, University of Florida, PO Box 110730, Gainesville, FL 32611-0730, USA.
*Corresponding author: rnsvarner@yahoo.com

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Abstract

Soil solarization is used to manage nematodes, pathogens and weeds, but relatively few studies have examined solarization effects on soil mineral nutrients, soil properties and plant tissue nutrients. This study was designed to optimize the duration of solarization treatment for the management of soil and plant nutrients and crop biomass in an agroecosystem utilizing an organic nutrient source. The experiment was a split-plot with treatment duration as the main effect and solarization as the sub-effect. Solarization treatments of 2-, 4- and 6-week durations began on sequential dates and concluded in mid-August. Immediately post-treatment, okra (*Hibiscus esculentus* L.) seedlings were transplanted into subplots for tissue nutrient analysis. Freshly chopped cowpea [*Vigna unguiculata* (L.) Walp.] hay was applied to the soil surface directly around the okra seedlings as an organic nutrient source. Immediately following solarization treatment, concentrations of soil K and Mn were higher, while Cu and Zn concentrations were lower in solarized soils than in non-solarized soils. Soil pH was slightly lower in solarized plots. Concentrations of K, N, Mg and Mn in okra leaf tissue were higher in solarized plots than in non-solarized plots, but concentrations of P and Zn were lower in plants grown in solarized soil. Okra biomass was three and four times higher in the 4- and 6-week solarization treatments than in non-solarized treatments. Based on data from this experiment, 4- and 6-week durations of solarization were optimal for increasing crop biomass. The data indicate that solarization has significant effects on soil and plant nutrients. Results of the nutrient analyses suggest that the availability of nutrients from an organic source was not limited by solarization.

Key words: nutrient availability, organic agriculture, soil fertility, soil solarization, sustainable agriculture

Introduction

Soil solarization is the passive solar heating of soil under clear plastic mulch to reach high temperatures lethal to soil-borne pests[1]. Soil solarization has been used to successfully manage soil-borne pests including fungal and bacterial pathogens, nematodes and weeds[2–5]. Use of solarization has increased crop yields at sites with various pest problems[1–4]. Solarization may cause an increased growth response in plants not only due to reductions in soil pathogens but also due to changes in chemical or physical properties of the soil[6,7], including increased availability of mineral nutrients[1,8]. However, in one recent study, no differences were found in macronutrient concentrations between solarized and non-solarized soil[9].

Studies on solarization effects on soil properties and soil mineral nutrients have shown mixed results. In one study, concentrations of Ca, K, Na and Mg, and soil electrical conductivity increased consistently after solarization, while pH and P concentration remained the same or changed inconsistently[6]. In this same study, large increases in the concentrations of NO_3^- and NH_4^+ occurred, which may have been the result of increased mineralization of organic matter in the soil[6]. A follow-up study found twice as much mineralized organic matter in solarized soils as in untreated soils[10]. Stapleton et al.[7] found similar increases in NO_3^-, NH_4^+, Ca and Mg concentrations with solarization in four soil types in California[7]. Contrary to the findings of Chen and Katan[6], Stapleton et al.[7] found an increase in P concentration, no change in K concentration and inconsistent results with electrical conductivity. A more recent study[8] confirmed the previously published increases in soil concentrations of K, Ca and Mg, and also found lower pH in solarized soil. Discrepancies among studies are possibly

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due to differences in soil types, sampling depth and assay procedures[7].

Studies examining the effects of solarization on soil chemistry and physical properties have included an examination of these effects on plant nutrition. Tomato (*Lycopersicon esculentum* Mill.) seedlings grown in solutions from solarized and non-solarized soils and in pure water increased in height, leaf length and whole plant dry weight when grown in solution from solarized soil[6]. In another study, a 33% increase in fresh weights of Chinese cabbage (*Brassica rapa* L. 'Lei Choi') was observed in solarized versus untreated soil, with a further increase of 28% if solarized treatments were fertilized[7]. The authors concluded that the increases in plant growth may be attributed to a combination of pathogen reduction, increases in available soil nutrients and other ecological factors caused by solarization[7]. Another study found an increase in the concentrations of N and Cu in leaf tissue of tomato plants grown in solarized soil and a positive correlation between leaf dry weight and leaf concentrations of N, K and Cu[8]. Stapleton et al.[7] also included plant tissue analysis but there were no consistent differences in leaf tissue nutrient concentrations among treatments. This inconsistency could be a classical example of yield increases without changes in mineral nutrient concentration, a phenomenon that occurs because, as mineral nutrients become available from the mineralization of soil organic matter, nutrient concentrations are diluted within the increased plant biomass.

The objective of our research was to examine solarization effects on soil mineral nutrients, properties and crop health. It was also designed to include an examination of solarization effects on plant tissue nutrients. An additional objective was to determine the effects of solarization on plant nutrition in a system that utilized an organic nutrient source.

Materials and Methods

The experimental site was located at the University of Florida Plant Science Research and Education Unit (PSREU) near Citra, Florida, and the study was conducted during summer of 2003. The soil at the study site was a hyperthermic, uncoated typic Quartzipsamments of the Candler series with a 0–5% slope[11]. Measured soil texture was 95% sand, 2% silt and 3% clay. Measured soil pH prior to the experiment ranged from 5.5 to 6.0 with an average of 5.9. The field was prepared with a crimson clover (*Trifolium incarnatum* L. 'Dixie') cover crop during the winter season and disked 2 days before raised beds were constructed.

The experiment was a split-plot design in which the main effect was duration of treatment and the sub-effect was solarization. Five replicates were arranged in a randomized complete block design on the main effect. Each experimental plot was a raised bed 6 m long, 1 m wide and 20 cm high. The bed soil was moistened by overhead irrigation if it was not sufficiently moist before plastic application. The solarization treatment was installed using a single layer of clear, 25-μm-thick, UV-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC). Solarization treatments and non-solarization control (without plastic) treatments of 2, 4 and 6 week durations were conducted during July and August. The treatments began on sequential dates and concluded on 12 August 2003.

Soil sampling and analysis

Six soil cores, 2.5 cm in diameter and 15 cm deep, were collected from each plot immediately after the conclusion of solarization treatment (0 days post-treatment). The samples were air-dried and sieved through a 2-mm stainless steel screen. Nitrogen concentration was determined from soil samples using a modified micro-Kjeldahl procedure[12] and further modified by treating a 2-g soil sample using a 380°C digestion in a mixture of concentrated H_2SO_4, H_2O_2 and K_2SO_4 : $CuSO_4$ salt-catalyst mixture[13,14]. Soil nutrients were extracted by the double-acid procedure[15]. Soil Ca, Mg, Cu, Fe, Mn and Zn were determined by atomic absorption spectrometry, soil K by atomic emission spectrometry and soil P by colorimetry. Soil pH was measured at a 2 : 1 water to soil ratio using a glass electrode[16]. Mechanical analysis was used to determine percent sand, silt and clay using a soil hydrometer method[17,18]. Organic matter content ($g\,kg^{-1}$) was determined using the Walkley–Black method[19,20]. Cation exchange capacity (CEC) was determined by the summation method of relevant cations[21,22].

Crop management and nutrient analysis

Okra (*Hibiscus esculentus* L. 'Clemson spineless') seeds were planted and germinated in a growth room, then moved to a greenhouse for maturation. Seedlings were watered and fertilized with a 20 : 20 : 20 ($N : P_2O_5 : K_2O$) mix as needed for 5 weeks. One week after the conclusion of solarization treatments, 5-week-old okra seedlings were planted in the experimental plots. An organic fertilizer consisting of green cowpea [*Vigna unguiculata* (L.) Walp. 'Iron Clay'] hay was applied on the soil surface to the area immediately around the okra seedlings at a rate of $3.5\,kg\,m^{-2}$. The hay was obtained from a cowpea cover crop grown in an adjacent field, which was cut at the early bloom stage, and immediately applied to the plots. The cowpea tissue was analyzed for nutrient concentration from samples collected at the time of application. The okra plants were harvested 6 weeks after planting, at early flowering. Dry whole plant biomass was measured, and the youngest, fully expanded okra leaves were collected for nutrient analysis.

For the nutrient analysis of both okra (youngest, fully expanded leaves to make 0.5 g dried) and cowpea (chopped green hay), plant material was weighed, dried, reweighed and ground to pass a 2-mm stainless steel screen using a Wiley mill. Plant material was ashed in a muffle furnace at

Table 1. Extractable soil mineral nutrient concentrations from 2003 summer solarization experiment (0 days post-treatment).

	Soil nutrient concentrations ($mg\,kg^{-1}$)											
Time[1]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	----------N----------			----------P----------			----------K----------			----------Mg----------		
2 weeks	406	340 B[2]*	373	38.9	38.1	38.5	21.4 C	22.7	22.1	10.8	13.0	11.9
4 weeks	385	408 A	397	38.6	46.5	42.6	37.0 A	21.4*	24.2	11.8	9.0	10.4
6 weeks	381	406 A	394	40.3	47.6	44.0	30.6 B	26.9	28.8	14.5	15.8	15.2
Mean	391	385		39.3	44.1		26.4	23.7		12.4	12.6	
	----------Zn----------			----------Cu----------			----------Mn----------					
2 weeks	1.2	1.4	1.3	0.25	0.27 B*	0.26	2.1	2.0	2.0			
4 weeks	1.4	1.4	1.4	0.26	0.29 AB*	0.28	2.2	2.0	2.1			
6 weeks	1.3	1.5	1.4	0.24	0.31 A*	0.28	2.4	1.7	2.1			
Mean	1.3	1.5**		0.25	0.29		2.2	1.9*				

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter in a column indicates no significant differences.
* and ** indicate significant differences between solarized and non-solarized at $P < 0.05$ and 0.01, respectively. No symbol indicates no significant difference.

480°C for a minimum of 4 h and treated with HCl in preparation for nutrient analysis[13,14]. Nitrogen was determined using a method similar to that used for the soil samples, except that a 100-mg sample was used and boiling beads were added to the samples before being placed on the aluminum block digester[12–14]. Leaf tissue concentrations of Ca, Mg, Cu, Fe, Mn and Zn were determined by atomic absorption spectrometry, K by atomic emission spectrometry and P by colorimetry.

Statistical analysis

Okra biomass, okra leaf nutrient concentration and extractable soil nutrient data were compared among durations and between solarized and non-solarized treatments using analysis of variance (ANOVA). If significant differences were detected among duration treatments, means were separated using a least significant difference (LSD) test at the $\alpha = 0.05$ level. All data were analyzed using MSTAT-C software (Michigan State University, East Lansing, MI; 1989).

Results

Soil mineral nutrients

The concentrations of several soil mineral nutrients and soil properties responded to solarization treatment. However, no significant differences were found among any treatments for concentrations of P and Mg in soil (Table 1). Calcium and Fe were also monitored but were not affected by treatment either in soil or in plant tissue (data not shown). Across all plots, the concentration of soil Ca averaged 110.8 and Fe averaged 10.6. A significantly higher concentration of Mn was found in the soil of solarized treatments ($P < 0.05$, Table 1). Zinc concentration and organic matter ($g\,kg^{-1}$) were lower in solarized treatments, although not significantly ($P < 0.10$; Tables 1 and 2).

Significant interactions of solarization treatment × duration occurred with N, K, Cu and pH (Tables 1 and 2). Nitrogen was 19% higher in the 2-week solarized treatment compared to the 2-week non-solarized treatment and about 16% lower in the 2-week non-solarized compared to the 4- and the 6-week non-solarized treatments ($P < 0.05$). Potassium was 73% higher in the 4-week solarized treatment compared to the 4-week non-solarized treatment ($P < 0.05$). Among the treatments involving durations of solarization, K was highest in the 4-week treatment and lowest in the 2-week treatment ($P < 0.05$). Copper was lower ($P < 0.05$) in solarized treatments compared to non-solarized treatments regardless of duration, and Cu was higher in the 6-week non-solarized treatment than in the 2-week non-solarized treatment ($P < 0.05$). We found slightly lower pH in solarized plots of 2- and 6-week durations compared to non-solarized plots (Table 2). Soil pH was highest in the 6-week non-solarized treatment compared to the 2- and 4-week non-solarized treatments ($P < 0.05$). With the exception of K (Table 1), no mineral nutrients or soil properties were affected by the duration of solarization treatment.

Okra leaf tissue nutrients

Several okra leaf tissue nutrient concentrations (N, P, K, Mg, Na, Zn and Mn) changed with solarization treatment. Foliar N concentration was also higher in solarized treatments than in non-solarized ($P < 0.05$) and concentration decreased as duration of treatment increased ($P < 0.01$). The concentration of K in okra leaf tissue was 40% higher in solarized treatments compared to non-solarized treatments ($P < 0.01$; Table 3).

Table 2. Soil properties from 2003 summer solarization experiment (0 days post-treatment).

	Soil pH			CEC (cmol kg^{-1})			Organic matter (g kg^{-1})		
Time[1]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2 weeks	5.2	5.3 B[2]*	5.3	2.7	2.5	2.6	10.5	11.0	0.7
4 weeks	5.3	5.3 B	5.3	2.6	2.6	2.6	10.6	12.2	11.4
6 weeks	5.3	5.6 A*	5.4	2.9	2.7	2.8	11.5	12.0	11.8
Mean	5.3	5.4		2.7	2.6*		10.9	11.7+	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter indicates no significant difference.
+ and * indicate significant differences between solarized and non-solarized at $P < 0.10$ and < 0.05. No symbol indicates no significant difference.
CEC, cation exchange capacity.

Table 3. Okra leaf tissue nutrient concentrations at conclusion of 2003 summer solarization experiment (59 days post-treatment).

	Okra leaf nutrient concentrations								
Time[1]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	----------N (g kg^{-1})----------			----------P (g kg^{-1})----------			---------K (g kg^{-1})----------		
2 weeks	41.2	38.6	39.9 A[2]	4.3 AB	4.4 B	4.3	33.4	28.2	30.8
4 weeks	37.3	29.2	33.3 B	4.9 A	4.9 B	4.9	38.1	22.2	30.2
6 weeks	30.1	29.2	29.7 B	4.0 B	5.6 A*	4.8	33.4	24.3	28.9
Mean	36.2	32.3*		4.4	5.0		35.0	24.9**	
	---------Mg (g kg^{-1})---------			----------Zn (mg kg^{-1})----------			----------Mn (mg kg^{-1})----------		
2 weeks	7.0	8.4	7.7	102	102	102	442	327	385
4 weeks	7.6	7.3	7.4	123	129	126	515	440	478
6 weeks	6.1	8.7*	7.4	99	139*	119	518	373	445
Mean	6.9	8.1		108	123		492	380*	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter indicates no significant difference.
* and ** indicate significant differences between solarized and non-solarized at $P < 0.05$ and 0.001, respectively. No symbol indicates no significant difference.

There were significant interactions between solarization duration and treatment for several foliar nutrients (Table 3). Phosphorus concentration was 29% lower in the 6-week solarized treatment compared to the 6-week non-solarized treatment. Among non-solarized treatment durations, the 6-week treatment was higher than the 2- and 4-week treatments ($P < 0.05$). Among solarized treatments, P was higher in the 4-week treatment than in the 6-week treatment ($P < 0.05$). Magnesium was 30% lower in 6-week solarized treatments compared to 6-week non-solarized treatments ($P < 0.05$).

Of the micronutrients that showed significant changes in leaf tissue, the concentration of Zn showed a similar pattern to P and Mg and was 29% lower in the 6-week solarized treatment than in the 6-week non-solarized treatment ($P < 0.05$). The concentration of Mn in leaf tissue was 29% higher in solarized treatments than non-solarized treatments ($P < 0.05$). Further analysis indicated that soil Mn concentration and leaf tissue Mn concentration were highly correlated ($r = 0.587$, $P < 0.01$).

Okra biomass

Dry whole plant biomass of the okra crop was more than three times higher in the 4-week solarized treatment and four times higher in the 6-week solarized treatment compared to the non-solarized treatments of the same duration ($P < 0.01$; Table 4). Okra biomass was 67% lower in the 6-week non-solarized compared to the 2-week non-solarized treatment ($P < 0.05$).

Discussion

Solarization affected the chemistry and properties of the soil in treatment areas. Extractable N was higher in 2-week solarized soil. The concentration of K was higher in the 4-week solarized soil compared to non-solarized soil. The occurrence of a maximum level of K in 4-week solarized soil among the three solarization treatment durations was interesting and somewhat unexpected. Activity of many soil micro-organisms increases with temperature[23], so we

Table 4. Dry okra biomass at conclusion of summer solarization experiment (56 days post-treatment).

	Dry weight of okra biomass (g plot^{-1})		
Time[1]	Sol	Non	Mean
2 weeks	181.0	161.8 A[2]	171.4
4 weeks	247.4	81.6 AB**	164.5
6 weeks	221.1	54.1 B***	137.6
Mean	216.5	99.2	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test; no letter in a column indicates no differences at $P < 0.05$.
** and *** indicate significant differences between solarized and non-solarized at $P < 0.01$ and 0.001, respectively.

may expect more decomposition of the cowpea hay and therefore more release of K as the duration of solarization increases. Therefore the lowest level of K in 2-week solarized soil would be expected, but the decrease in 6-week solarized soil was not. Potassium is a highly leachable nutrient[24], and therefore would be subject to loss once it is mineralized from the organic hay. Because the 6-week solarization was started 2 weeks earlier than the 4-week solarization (in order to synchronize the okra planting date), the substantial amounts of K mineralized during the initial several weeks of solarization would have occurred 2 weeks earlier in the 6-week solarization treatment. If a significant rainfall event occurred during this time, it is possible that some of the mineralized K was leached. Leaching may be limited because the beds were covered with clear plastic; however, the soil beneath may become saturated during a heavy rainfall event, which may allow for some leaching to occur. Manganese concentration was higher in solarized soil in general. We also saw a lower concentration of Cu with solarization treatment, a finding that is consistent with earlier research[7]. Zinc decreased with solarization as well. We found consistently lower pH in solarized soils compared to non-solarized soils, which confirms earlier research[8]. These differences in soil pH between treatments were small however (maximum difference was only 0.3; Table 2), and may not be biologically important.

Some prior solarization research examining plant tissue found no significant differences in nutrient concentrations, which was likely due to a mineral dilution effect[7], while others found an increase in K, N, Ca and Mg[8]. In the current experiment, K concentration in leaf tissue increased with solarization treatment. This increase likely reflected the quick mineralization of soil organic matter and luxury consumption of K above that required for plant growth[25]. Leaf tissue concentrations of N and Mn increased in solarized treatments, while Mg, P and Zn decreased. Because the sum of the total cations (K, Ca and Mg especially) on an equivalent basis tends to remain constant in plant leaf concentration, an increase in plant absorption of K will result in a decrease in Mg even when sufficient soil Mg is available[26,27].

The increase in N and Mn in leaf tissue may reflect the increase of these nutrients in solarized soil from the cowpea hay, and may also be considered an indication of overall plant health. Solarization affects a wide range of organisms in the soil[1] and an increase in amino acid synthesis following solarization, which may suggest an increase in microbial activity, has been observed[10]. Data from the current study suggest that solarization did not harm organisms involved in nutrient cycling sufficiently to impair nutrient release and uptake from an organic nutrient source.

Okra biomass tripled in the 4-week solarized treatment and quadrupled in the 6-week solarization treatment compared to the non-solarized treatments of the same duration. The increase in okra biomass in 4- and 6-week solarized treatments is in part due to a decrease in weed competition by solarization[28] and a reflection of overall plant health. The higher concentrations of N and K in leaf tissue indicate that solarization increases the uptake of these essential nutrients in biomass production, even in agroecosystems utilizing an organic nutrient source. Since crop yield of okra is closely related to plant biomass[29], solarization treatments would increase okra yield if the plants had been maintained through harvest. The data suggest that solarization durations of 4 and 6 weeks are equally effective and significantly better in increasing crop biomass than the 2-week solarization treatment.

Conclusions

In general, the changes in soil mineral nutrients were reflected in changes in leaf tissue nutrients, particularly N, K, Mn and Zn. Overall, concentrations of some essential nutrients, including N, K and Mn, were higher with solarization treatment. This increase in nutrients was reflected in the leaf tissue analysis and increased biomass that indicated an improvement in crop health due to solarization. The increase in okra biomass in solarization treatments of 4- and 6-week durations indicates that okra plants utilized the increased nutrients available and that solarization did not limit the nutrient availability from an organic nutrient source. This study also indicates an increased growth response that may involve changing soil chemical and physical properties, which adds to the benefits of using solarization for soil-borne pest management.

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Maize silage as an energy supplement in organic dairy cow rations

Margit Velik*, Roswitha Baumung, and Wilhelm F. Knaus

Department of Sustainable Agricultural Systems, Division of Livestock Sciences, BOKU—University of Natural Resources and Applied Life Sciences, Gregor Mendel Straße 33, 1180 Wien, Austria.
*Corresponding author: margit.velik@boku.ac.at

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Abstract

The literature implicates strongly that including energy supplements in dairy rations based on protein-rich forages increases performance and feed efficiency due to an improved and more balanced ruminal energy and protein supply. Therefore, both conventional and organic dairy farms primarily supplement roughages with concentrates, containing high proportions of cereal grains. However, considering the main principles of sustainable agricultural systems and nutrient cycles, the question of alternatives is raised. Therefore, the present study was conducted to compare grain and maize silage as energy sources in organic dairy cow rations. Two grass–clover silage-based diets, offered on an *ad libitum* basis, were supplemented either with 1 kg grain mixture plus 0.5 kg hay (treatment group G) or 2.1 kg maize silage (treatment group M) on a dry matter (DM) basis. The trial was carried out as a change-over design and lasted for 15 weeks. Intake of concentrates, DM and utilizable crude protein in the duodenum (uCP) were similar in both treatments. However, significant differences between treatments G and M were found for grass–clover silage dry matter intake (DMI) (13.4 versus 12.9 kg), forage DMI (14.6 versus 15.7 kg), crude protein (CP) intake (2885 versus 2801 g), ruminal nitrogen balance (RNB) (40 versus 29 g) and intake of neutral detergent fiber (NDF) (7630 versus 7900 g). Milk yield was not affected by treatment, but in treatment M, milk fat content was at 42.4 g kg^{-1}, significantly higher, and milk urea concentration at 19.7 mg 100 ml^{-1}, significantly lower, as compared with treatment G. Efficiency of N use (N in milk in % of N intake) tended to be improved in treatment M. Balances of energy and uCP (intake as a percentage of requirements) were unaffected by treatment.

Key words: dairy cow, organic farming, energy supplement, maize silage, protein, milk composition

Introduction

In organic dairy farming systems, grass, legumes and their ensiled conserves represent the main feedstuffs and major protein sources. In ruminant nutrition, ruminal microbes contribute considerably to the protein supply of the animal. For an optimal growth of rumen microbes and synthesis of microbial protein, a balanced and simultaneous ruminal protein and carbohydrate supply is crucial[1]. Carbohydrates can be divided into non-structural carbohydrates (starch, sugar and pectins), which are readily fermentable in the rumen, and structural carbohydrates (cell wall constituents consisting of cellulose, hemicellulose and lignin), which are potentially degradable in the rumen. Both determine the energy value of a feedstuff. From grass, legumes and their silages, rumen protein supply is usually higher than energy supply and, most notably, protein degradation occurs more rapidly than carbohydrate fermentation. Therefore, slow ruminal carbohydrate degradation rate in relation to rapid nitrogen release is claimed as one of the main factors for high environmental nitrogen losses, low microbial protein synthesis and low feed efficiency[2].

Traditionally, protein-rich dairy diets are supplemented with cereal grains, which are high in starch and low in protein content. However, in sustainable agriculture systems, feeding grain must be viewed critically with regard to amount of forage utilization, intact nutrient cycles and the use of potential human food in animal feeding. Therefore, in the past decade, several studies examined alternatives to grain such as fodder beets, beet pulp, whole crop silages, maize silage or energy-rich by-products[3–7]. A nutritional consequence when substituting cereals is that starch is replaced by other carbohydrate sources.

The general aim of organic dairy farming is to reach a high level of self-sufficiency. This can be achieved by minimizing purchased concentrate use and focusing on milk production from forage. Therefore, on organic dairy farms, maize silage could be an attractive crop instead of

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Table 1. Chemical composition and calculated nutritive values of feeds (g kg^{-1} dry matter (DM) unless stated).

Component	Grass–clover silage	Hay	Concentrate mixture	Maize silage	Grain mixture
DM	466	870	863	300	869
Crude protein	160	110	171	76	107
Crude ash	119	72	61	40	21
Crude fiber	220	283	82	200	33
Crude fat	29	22	26	31	24
Starch	ND[1]	ND	414	304	673
NDF_{org}	430	586	309	452	171
ADF_{org}	279	336	118	232	45
NEL (MJ kg^{-1} DM)	6.0	5.4	7.5	6.5	8.5
uCP[2]	136	121	171	130	165
Ruminal N balance	3.8	−1.7	0.0	−8.7	−9.3

[1] Not determined.
[2] Utilizable crude protein in the duodenum.

cereal grains. Maize silage is a reliable forage supplement that can be grown in most grassland regions of moderate altitude. It supplies ruminally digestible fiber, but also noteworthy amounts of ruminally degradable starch[8]. Therefore, the objective of this experiment was to evaluate whether grain and maize silage are interchangeable energy sources in grass–clover silage-based diets in terms of feed and nutrient intake, milk yield, milk constituents and feed efficiency.

Animals, Materials and Methods

Experimental design and animals

The experiment was conducted as a repeated change-over design at the organic farm of the Agricultural High School Ursprung in the province of Salzburg, Austria (570 m NN, 1250 mm precipitation, 8.5°C average annual temperature) from November 2005 to February 2006. The experiment was carried out with 13 Holstein Friesian dairy cows, housed in a cubicle housing system with Calan gates for individual feeding. Cows were allotted to two treatment groups (six cows in treatment G and seven cows in treatment M) according to milk yield, days in milk and number of lactations. At the beginning of the experiment, average (± standard deviation) milk yield, days in milk and number of lactations were 25.9 ± 6.16 kg per day, 105 ± 59.0 days in milk and 2.9 ± 1.82, respectively. The experiment lasted for 15 weeks with a 3-week adaptation period to Calan gates and feeding regimen at the beginning of the experiment and a change-over period of 2 weeks in weeks 9 and 10.

Feeding regimen

In the experiment, two grass–clover silage-based rations, intended to be equal in dietary energy content, were compared. The chemical composition and nutritional values of the feeds are listed in Table 1. Grass–clover silage was a mixture of first and third cut and derived from approximately 50% grassland and 50% perennial clover–grass leys. Hay was harvested from second cut. Maize silage was harvested in mid-October, chopped to lengths of approximately 10 mm and ensiled as bales. The grain mixture consisted of equal amounts of barley, wheat, rye and maize, which represent commonly used energy sources in concentrates for dairy cows. Furthermore, 50 g of a commercial mineral and vitamin mixture were given to each cow daily.

Both diets were based upon *ad libitum* allowance of grass–clover silage, which was fed at 5 : 00 and 15 : 30. At 14 : 00, approximately 1.5 kg hay was provided for each cow. All feeds were removed and weighed before the next feeding. Treatment group G received 1 kg of the grain mixture and treatment group E 2.1 kg maize silage on a dry matter (DM) basis. Grain mixture and maize silage were fed on top of grass–clover silage in two equal portions at morning and evening feeding. Additionally, cows in treatment G were fed 1 kg hay in addition to grass–clover silage at morning feeding to decrease grass–clover silage intake. It was assumed that the grain mixture and the maize silage were consumed completely. Refusals of morning-fed hay in treatment G were manually collected and weighed before removing grass–clover silage. In the present paper, maize silage, the grain mixture and morning-fed hay are referred to as supplements. In both treatments, cows exceeding a daily milk production of 17 kg were fed a purchased, pelleted concentrate mixture at a rate of 1 kg DM per 2 kg additional milk yield via an automatic feeding station.

Data collection and analytical procedures

Individual forage intake was recorded during four 6-day recording periods in weeks 4, 8, 11 and 15 of the experiment using Calan gates. Grass–clover silage was offered twice a day to ensure refusals in amounts of 5–10%. Orts were weighed before next feeding. Intake of the concentrate mixture was recorded daily during the whole experiment. In each recording period, DM content of all used feeds and

Table 2. Effect of maize silage versus grain-mixture on daily feed and nutrient intake.

Item	Lsmeans		s_e	P
	Treatment G	Treatment M		
Hay DMI (kg)	1.2	0.7	0.37	< 0.001
Hay DMI morning feeding (kg)	0.5	–		
Concentrate DMI (kg)	3.0	3.0	0.45	0.916
Total DMI (kg)	18.6	18.7	2.19	0.599
Total DMI kg body weight$^{-0.75}$ (g)	145	145	16.6	0.910
Forage DMI (kg)	14.6	15.7	1.70	< 0.001
Grass-clover silage DMI (kg)	13.4	12.9	1.67	0.005
NEL intake (MJ)	118	117	10.7	0.726
CP intake (g)	2885	2801	277.3	0.011
uCP intake (g)	2637	2618	240.7	0.506
Ruminal N-balance (g)	39.5	29.1	6.83	< 0.001
Crude fiber intake (g)	3551	3691	375.7	0.002
NDF_{org} intake (g)	7630	7900	763.6	0.003
ADF_{org} intake (g)	4532	4672	483.6	0.014
Crude fat intake (g)	522	541	52.0	0.003

feed refusals (grass–clover silage and hay) was determined at least three times by oven drying at 105°C for 24 h. Furthermore, in each recording period, one sample of each dietary component and feed refusal (for each treatment separately), pooled over 3 days, was collected and analyzed using methods described by ALVA[9] and VDLUFA[10]. Contents of utilizable crude protein in the duodenum (uCP) and energy were calculated according to GfE[11]. Cows were milked twice daily at 6 : 00 and 16 : 30 in a herring milking parlor and milk yields were recorded automatically at each milking. In each recording period, three pooled samples from morning and evening milk were collected from each cow and analyzed for fat, protein, lactose, urea and somatic cell counts. Between recording periods, individual milk samples were collected once a week. Body weights and body condition scores (BCSs) (1–5 points, 0.25 interval, 1: very lean, 5: very fat) were determined once in each recording period.

Statistical analysis

Data were analyzed with the statistical program package SAS[12] according to the model developed by Kaps and Lamberson[13]. However, only parameters which were statistically significant were included in the final reduced model. Statistical differences were considered to be significant when $P < 0.05$ and trending towards significance when $P < 0.10$.

$$Y_{ijklmn} = \mu + \alpha_i + \beta_k + \gamma_l + \delta_m + \mathrm{SUB}(\beta)_{jk} + \varepsilon_{ijklmn},$$

where Y_{ijklmn} = observation on cow j with treatment i, order of treatment k and period l, μ = overall mean, α_i = fixed effect of treatment i (G, M), β_k = effect of order k (I, II) of applying treatments, γ_l = fixed effect of period l (1, 2, 3, 4), δ_m = continuous covariate day of experiment m, $\mathrm{SUB}(\beta)_{jk}$ = random effect of cow j within order k, ε_{ijklmn} = random residual error.

Results and Discussion

Several studies have examined the supplementation of protein-rich forages (pasture, grass silage and legume silage) with maize silage[14–16]. Other trials have compared different carbohydrate sources in dairy cow diets[3,4,17–19]. However, surveys comparing grain and maize silage as supplements are rare. In the present study, cows were fed grass–clover silage-based diets, which were supplemented either with 1 kg of a grain mixture plus 0.5 kg hay (treatment G) or 2.1 kg maize silage (treatment M) on a DM basis. Dietary energy content was similar in both treatments (6.4 and 6.3 MJ net energy for lactation (NEL) kg^{-1} DM in treatments G and M, respectively). Generally, it is assumed that at low levels of supplementation, the energy source has only little effect on feed intake, milk yield and milk composition[20]. Hence, most studies cited in the present paper used much higher supplementation rates than the study at hand.

Feed and nutrient intake

Maize silage and grain differ in their nutritional characteristics, especially in their contents of starch and fiber (Table 1). Generally in maize silage, the B1 fraction (starch) of the CNCPS (Cornell net carbohydrate and protein system) is lower as compared with cereal grain (40 versus 70% of carbohydrates) and the B2 fraction (hemicellulose and cellulose) higher (45 versus 20% of carbohydrates)[21,22].

Daily forage dry matter intake (DMI) (grass–clover silage, hay and maize silage) was significantly higher in treatment M (15.7 versus 14.6 kg DM). Grass–clover silage intake was 0.5 kg DM lower in treatment M as compared with treatment G (Table 2). However, in the present study, DMI and energy content of supplements were different and no data for a treatment group without supplementation were

Table 3. Effect of maize silage versus grain-mixture on daily milk yield and milk composition.

Item	Lsmeans		s_e	P
	Treatment G	Treatment M		
Milk (kg)	23.3	23.1	1.57	0.360
ECM (kg)	23.1	23.3	1.86	0.431
Protein ($g\,kg^{-1}$ milk)	32.0	31.8	1.25	0.197
Fat ($g\,kg^{-1}$ milk)	40.9	42.4	4.10	0.012
Lactose ($g\,kg^{-1}$ milk)	47.2	47.9	11.38	0.617
Fat protein ratio	1.28	1.33	0.124	0.004
Protein yield (g)	733	729	54.9	0.559
Fat yield (g)	949	974	109.5	0.094
Somatic cell counts ($\times 10^3\,ml^{-1}$)	98	106	107.2	0.611
Urea ($mg\,100\,ml^{-1}$)	20.8	19.7	3.74	0.035

Table 4. Effect of maize silage versus grain-mixture on feed utilization.

Item	Lsmeans		s_e	P
	Treatment G	Treatment M		
Concentrate mixture[1] (g DM kg^{-1} milk)	164	115	22.6	< 0.001
N efficiency[2] (%)	25.5	26.1	16.39	0.075
Milk from forage[3] (%)	70	82	2.8	< 0.001
uCP balance[4] (%)	113	113	6.5	0.788
NEL balance[4] (%)	105	104	8.8	0.264

[1] Concentrate mixture and grain mixture.
[2] N in milk in % of N intake.
[3] (NEL $intake_{forage}$ − NEL $requirement_{maintenance}$)/NEL requirement kg^{-1} milk.
[4] Intake as a percentage of requirements for maintenance and milk production.

available. Hence, with the present results, no reliable statement for substitution rates can be made. Intake of the concentrate mixture averaged 3.0 kg DM in both treatments. Therefore, percentage of dietary forage intake was rather high ($P < 0.01$) at 79% of total daily DMI in treatment G and 85% in treatment M, taking into account an average milk yield of 23.2 kg per day.

No difference between treatments was observed for total daily DMI, estimated intake of NEL and uCP (Table 2). Contrary to uCP intake, intake of CP was significantly lower in treatment M, which resulted in different dietary CP concentrations (15.7 and 14.9% of DM in treatments G and M, respectively, $P < 0.01$). RNB is an estimated value for the protein supply of the ruminal microbes and is calculated as CP minus uCP divided by 6.25[11]. RNB was significantly lower in treatment M (29 versus 40 g), which reflected the lower CP intake in treatment M (Table 2).

In the study in question, protein balance, defined as uCP intake as percentage of requirements for maintenance and observed milk production[11], was markedly positive (+13%) in both treatments. Reasons for the positive protein balance could be the following: provision of grass–clover silage *ad libitum* for the whole day, a slight overestimation of the uCP feed value as well as discrepancies in the estimation of the protein and energy requirements of the GfE[11].

Overall hay intake was, according to plan, significantly higher in treatment G (1.2 versus 0.7 kg DMI); however, intake was considerably lower in both groups (6 and 4% of total daily DMI in treatments G and M, respectively) than initially planned and expected. Although treatment G was supplemented with hay at morning feeding, daily intake of crude fiber, NDF_{org} and ADF_{org} was on average 3–4% higher in treatment M, which was statistically significant (Table 2). This reflected mainly differences in the fiber content of the two energy supplements (fiber intake from maize silage was 50% higher than fiber intake from grain mixture plus hay consumed at morning feeding).

Milk production and feed efficiency

Several authors have dealt with the effect of different carbohydrate supplements on milk yield and milk composition. Inconsistency in the results is often attributed to differences in the source of carbohydrate, the quantity of supplementation and the forage quality. Generally, it is assumed that good roughage quality is likely to increase substitution rates and reduce production responses to supplements[23,24].

Results of the present study concerning milk performance and feed efficiency are shown in Tables 3 and 4, respectively. In the present study, daily milk yield was

unaffected by energy supplementation, which is in agreement with results of Castillo et al.[17] and Visser et al.[25], who fed concentrate mixtures with different structural and non-structural carbohydrates and did not observe any difference in DMI, energy intake or milk yield. Contrary to this, Moran and Croke[7] fed different amounts of maize silage or wheat to pasture-fed dairy cows at the same level of supplemental energy and observed numerically higher milk yields when feeding wheat. However, this might have resulted from the trend for higher supplemental ME intake and lower calculated pasture substitution in the wheat-fed treatment.

In the study at hand, milk protein content was unaffected by treatment, which agrees with results of Huhtanen et al.[6], but is contrary to those of Moran and Croke[7]. The present study showed a significantly higher milk fat content in treatment M ($P = 0.01$). However, this difference was only a trend for milk fat yield ($P = 0.09$). It is commonly agreed that the amount of ruminally fermentable fiber and consequently the production of acetic acids have a major impact on milk fat content. Nevertheless, several studies comparing fibrous versus starchy supplements did not report any effect on milk fat percentage[6,7,17], although NDF intake was significantly higher with fibrous carbohydrates.

In the present study, milk urea concentration was within the recommended range of 15–30 mg $100\,ml^{-1}$ in both treatments[26]. However, in treatment M, urea concentration was slightly but significantly lower (19.7 versus 20.8 g, $P = 0.04$). Hristov and Ropp[27] fed two diets supplemented either with ruminally fermentable non-structural carbohydrates (barley and molasses) or ruminally fermentable fiber (beet pulp, brewer's grain and corn) and found a significantly lower milk urea concentration for the ruminally fermentable fiber diet. However, whether the reduced urea content observed in the present study resulted from reduced protein intake, increased ruminally fermentable energy or improved ruminal N capture is unclear.

In general, the efficiency with which dietary N is utilized by dairy cows (N in milk in % of N intake) is low, ranging from 22 to 39%[2,28,29]. It is generally agreed that low dietary N efficiency is partly related to high dietary CP content and an unbalanced ruminal energy and protein supply, and that it can be improved through the supplementation of feedstuffs rich in carbohydrates[30,31]. The present study showed a slight tendency (26.1 versus 25.5%, $P = 0.08$) for an improved dietary N efficiency in treatment M. Unfortunately, in the present study, herd size was too small to allow for a third, non-supplemented treatment group; hence no statement for a diet without supplementation can be made.

With the data at hand, it is difficult to make a reliable statement on changes in body weight and BCS, because cows were in different stages of lactation and cows were not kept separated from water troughs and grass–clover silage before weighing. Generally, treatment did not show a significant effect on body weight, which averaged 649 kg ($P = 0.56$), and BCS, which averaged 3.2 points in both treatments ($P = 0.83$). The lack of differences in body weight and BCS between treatments may be partly because of the rather low amount of supplements fed and partly because of the lack of difference in DMI and NEL intake.

Conclusions

The present study gives an indication that with even small amounts of supplemental energy nutrient intake, protein supply and milk composition can be influenced. Although only 11% of total DMI was fed as maize silage, CP intake was significantly reduced, RNB and milk urea concentration significantly decreased, and dietary N efficiency slightly improved as compared with the grain-supplemented treatment. However, with the present trial, no reliable statement can be made whether these improvements are due to reduced CP intake, improved ruminal energy supply or greater ruminal N capture. Milk yield was not negatively influenced by feeding maize silage instead of grain; however, the dietary proportion of supplements was probably too small to observe responses in milk production. It is concluded that inclusion of small amounts of maize silage instead of grain did not seem to have any negative effects. However, higher supplementation rates and lower dietary CP contents might lead to greater differences.

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The barriers to further adoption of organic farming and genetic engineering in Australia: views of agricultural professionals and their information sources

Sarah Ann Wheeler*

Research Fellow, Centre for Regulation and Market Analysis, University of South Australia, City West Campus, North Terrace, Adelaide, 5001, Australia.
*Corresponding author: sarah.wheeler@unisa.edu.au

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Abstract

Research has shown that agricultural professionals are one of the major influences on farmer adoption of agricultural innovations. Genetic engineering and organic farming represent two vastly different innovations in agriculture, and both assert to have important sustainability outcomes. This paper presents the views from a telephone survey of agricultural scientists, extension officers and academics in Australia ($n = 185$) on the barriers to further adoption of organic farming and agricultural genetic engineering, as well as exploring where they obtain their information about the two innovations. Many professionals believe that market issues (in terms of small market size and the extent that consumers are willing to pay premiums) will limit the size of farmer adoption of organics in Australia, while on-farm issues (in terms of production difficulties and pest and disease problems) are named as the second largest barrier to further adoption. On the other hand, professionals from the targeted sample, who were more knowledgeable about organic farming, named information needs and lack of government support as the major barrier facing further diffusion of organic farming. In contrast, public attitudes and negative media portrayal are named as the largest barrier facing further adoption of genetic engineering in Australia. The uncertainty surrounding the research into genetic engineering (and the lack of long-term research) is believed to be the second largest barrier facing further diffusion of genetic engineering while market problems are seen as the third largest barrier.

Key words: organic farming, genetic engineering, agricultural professionals, barriers, information sources, technology adoption

Introduction

Organic farming and agricultural genetic engineering represent two innovations that may hold benefits for increased sustainability in agriculture, and therefore it is important to understand what barriers their future adoption may face. Although there has been considerable research conducted by economists, sociologists, anthropologists, educationalists and marketers into what influences the adoption of innovations in agriculture[1–6], there has been less work so far in looking at what influences sustainable farming techniques, or in particular, organic farming and genetic engineering products. This paper reports agricultural professionals' views on the barriers towards further adoption of organic farming and genetic engineering.

One of the main themes from the adoption literature is that adoption of sustainable techniques by landholders depends on their perceptions that the innovation will help serve their goals. Perceptions of issues are likely to vary between farmers, and they are unconsciously influenced in their selection, organization and interpretation of information via communication channels and social networks. Research shows sources that provide information to farmers about sustainable innovations have a very consistent and important influence on the adoption of innovations[3–4,7]. Sources that provide information about agricultural innovations to farmers include extension officers, scientists and academics. These professionals also play an important role by helping design policy to eradicate (or enforce) barriers to further diffusion of

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innovations. It is therefore important to know what professionals' beliefs are on the barriers to new innovations in agriculture, especially for innovations such as organic farming and genetic engineering, as much research tends to focus on farmers' beliefs[8].

Previous research by Duram[9] on what influences the adoption of organic agriculture has identified four key structural factors, namely: (1) economic: markets, agribusiness and independence, production costs and current level of organic farmers; (2) political: organic certification, agricultural policy and information sources; (3) social: family, human health, views of organic and conventional agriculture in society, social culture and environmental attitudes and (4) ecological: ecosystems, soil health and animal health. Lampkin and Padel[10] and Padel *et al.*[11] suggest that there are four key factors that drive (or hinder) the adoption of organic agriculture: (1) policy signals from government and other policy-related institutions; (2) market signals from consumers and the food industry; (3) access to information and (4) the removal of institutional blockages or antagonisms.

The Organic Farming Research Foundation (OFRF) in the United States has regularly surveyed organic farmers on issues surrounding organic farming. One of the questions they asked in 1995 (945 farmers surveyed) was what was seen as the greatest barrier to further organic conversion. Sixty-three percent of respondents named 'unco-operative or uninformed extension' officers[12]. In OFRF's 1998 national survey of organic farmers, the greatest barriers to organic farming included:

1. unco-operative or uninformed extension agents (24%);
2. cost of organically allowed inputs (20%);
3. distance or transport of organically allowed inputs (18%);
4. sourcing or finding organically allowed inputs (12%);
5. achieving desired yields (12%);
6. information on organic practices unavailable or hard to find (8%);
7. effectiveness of organically allowable inputs and methods (8%);
8. pressure from lenders to farm conventionally (8%);
9. personal lack of knowledge about organic practices (7%) and
10. social pressure from other farmers or community to farm conventionally (7%)[12].

These responses were not just limited to organic farmers in the US, there were other indications that Australian farmers felt very similarly about information barriers to organic farming in Australia[13]. Organic farmers clearly perceived information constraints (which is a supply constraint) as one of the largest barriers towards further organic adoption. Demand constraints (such as the need for a market or higher consumer willingness to pay for organic produce) were not mentioned; however, a variety of supply constraints were often named. Costs, yields and issues about obtaining organic inputs concerned over half of the farmers who responded.

Some research has been conducted on the perceptions of genetic engineering by consumers and the barriers towards its further diffusion[14,15]. Consumers' lack of willingness to pay for genetically engineered products (such as genetically modified bread or meat) is usually named as the number one constraint against the further adoption of genetic engineering[16]. The reason for consumers' negative attitude is commonly perceived by scientists as a lack of consumer knowledge[17]. This popular belief of scientists about the lack of consumer knowledge has been addressed in many studies[18,19]. The main conclusion from these studies is that although an increase in subjective knowledge does tend to lead towards more positive attitudes to biotechnology products, actual knowledge on the other hand is not a factor in significantly influencing views. Indeed, there are a number of scientists who have serious concerns about the health risks and consequences of eating genetically engineered food, and who point to the growing number of scientific studies that are finding evidence to support their concerns[20].

However, many scientists remain convinced that there are no health risks from eating genetically modified food and blame the media as the reason why consumers form negative opinions. Cronin and Jackson[21] interviewed a number of scientists about their views on the barriers towards further diffusion of genetic engineering. Scientists have often suggested that attitudes are linked to information sources. Be that as it may, writers have found clear differences between information sources used by conventional and organic farmers[22–24]. It has been found that organic and biodynamic farmers place more importance on books, organic institutions and other farmers than conventional farmers, while conventional farmers place more importance on government and conventional organizations[22]. Egri[22] concluded that both organic and conventional farmers tended to use information that supports and confirms their pre-held existing practices and biases. There has been little study on the information sources used by agricultural professionals in Australia, and this study explores the issue further. In addition, the aim of this study is to establish and compare the views of Australian public agricultural professionals on the barriers to further diffusion of genetic engineering and organic farming in Australia.

Methodology

A telephone survey was conducted in mid-2004 to elucidate a range of agricultural professionals' views on organic farming and genetic engineering. An agricultural professional was strictly defined as either providing agricultural advice to farmers; conducting agricultural specific farm research; or teaching agricultural courses at university. Hence, those surveyed included extension officers, researchers, scientists and academics. The sample frame for the survey consisted of two groups: one general and one targeted. The general group of agricultural professionals

was limited to State and Commonwealth bodies based in South Australia. These included Rural Solutions South Australia, the South Australian Research and Development Institute, the University of Adelaide, CSIRO Land and Water, CSIRO Plant Industry and Primary Industries and Resources South Australia. The targeted group was randomly sampled from a constructed database of professionals employed within public bodies across Australia who had actual organic agriculture experience (people were surveyed from the above named organizations as well as CSIRO, University of New England, University of Western Sydney, DPIWE Tasmania, DPI Victoria, DPI Queensland, NSW Agriculture and Department of Agriculture WA).

Survey personnel were randomly selected from each database until the minimum sample sizes were reached. In the general sample 119 professionals were randomly surveyed and 66 professionals were randomly surveyed in the targeted sample. The 185 interviews conducted with professionals represented an overall response rate of 96% and were statistically representative (using a 7% level of precision). For more detail on the survey method and general statistics of respondents, see Wheeler[25,26].

This study reports the answers by professionals on what they perceived as the main barriers to the further adoption of genetic engineering and organic farming in Australia, and what they named as their information sources on each innovation. Within the survey, there were two sections, one on organic agriculture and one on genetic engineering. Within these sections, professionals were asked:

> What do you think are the major barriers facing the further diffusion of organic farming (*or genetic engineering*) in Australia?

There was no prompting of responses by professionals with the provision of possible answers. A professional was free to respond with as many, or as few, barriers as they wished. Similarly they were free to provide one word or extensive discussion in their responses. The wide variety of barriers named by professionals was then divided up into five categories each, to allow for comparison between agricultural innovations and survey samples. The exact response by professionals is listed after each category in Tables 1 and 2. Some typical comments made by professionals are also detailed to help provide more information and understanding about their opinions.

After answering a variety of questions on genetic engineering and organic farming, professionals were then asked:

> What are the main sources where you have gained your knowledge of organic farming (*or genetic engineering*) from?

Again, there was no prompting of responses, and professionals were free to respond with as many, or as few, information sources as they wished. Most named two to three information sources.

Results

Beliefs about the barriers to the further diffusion of organic farming

The commonly cited barriers to further adoption of organic farming included market issues, on-farm issues, information needs and government support and farmer acceptance.

Respondents from the general sample were more likely to think that market issues (in terms of the size of the organic market) was the major barrier that hampered further diffusion of organic farming. A common response was that the willingness of consumers to pay for organic products was low. For example:

> *'The adoption of either organics or biotechnology will be driven by the market—they will determine whether it is accepted or not'.*

Unlike general respondents who saw the barriers as predominantly demand driven, targeted respondents tended to view the barriers to the adoption of organic farming as predominantly supply driven. They were much more likely to view information needs and the lack of government support as the major issue hindering further diffusion of organic farming. Many suggested that farmers who are interested in converting to organic farming need to have more help to do so (in terms of information provision, specialist extension support, farm demonstrations and policy support). For example:

> *'The biggest problem is the lack of government support for organic agriculture ... Government is completely schizo about the whole area of organics, whereas biotechnology is actively funded'.*
>
> *'Farmers need a lot more skills to farm organically than conventionally, it is more physical and needs more technical support'.*
>
> *'There are huge learning curves associated with converting, and farmers need a lot of information to be able to do so'.*

On-farm issues (in terms of farm profitability, economics, pest and disease management, animal health, etc.) was seen as the second largest barrier to the adoption of organic agriculture by both groups, although the general group viewed it as more critical than the targeted group.

> *'Organic farming is uneconomic, it is more risky and less reliable'.*
>
> *'Organics is simply not sustainable, hence will not be adopted by most farmers'.*

Issues associated with farmer acceptance of organic farming were named as the fourth largest barrier towards its further adoption. Of the remaining barriers named, some professionals lambasted the organic industry itself as being a barrier to further farmer adoption:

> *'The organic industry is a fragmented industry, with organic agriculture being a bit of a club ... only for insiders'.*

Table 1. Barriers named by professionals towards further adoption of organic farming (OF).

Barriers	Total % ($n = 185$)	General sample % ($n = 119$)	Targeted (OF experienced) % ($n = 66$)
1. Market issues	27.2	33.9	18.7***
Lack of consumer willingness to pay premiums	14.8	19.6	8.8
Lack of consumer knowledge/education	2.3	1.6	3.1
Small market/marketing issues	7.5	11.4	2.6
Small scale issues	2.5	1.2	4.1
2. Information needs and Government support/policy	27.2	20.8	35.2***
Large information needs	13.5	12.2	15.0
Lack of research and development	6.4	3.3	10.4
Conversion costs	2.5	2.4	2.6
Lack of extension/advice for OF	1.8	0.0	4.1
No overall research body or support	1.6	2.0	1.0
Bias from government/research bodies	0.2	0.0	0.5
Lack of practical farm demonstrations	0.2	0.4	0.0
Scientific research randomness	0.2	0.4	0.0
Misinformation from science about OF benefits	0.2	0.0	0.5
Scientific perception of OF	0.2	0.0	0.5
Training needs for agricultural professionals	0.2	0.0	0.5
3. On-farm issues	25.6	28.2	22.3*
Uneconomic/not profitable	13.7	18.8	7.3
Farm scale issues	3.0	2.9	3.1
Weeds	1.6	1.2	2.1
Produce appearance problems	1.1	1.6	0.5
Pest/disease problems	1.1	0.8	1.6
Lack of nutrients in organically farmed soils	1.1	0.4	2.1
Increased costs	1.1	0.4	2.1
Long-term sustainability problems	1.1	1.2	1.0
Animal health issues	0.5	0.0	1.0
Increased risk as a farming system	0.5	0.4	0.5
Difficulty in only using certified inputs	0.2	0.4	0.0
Lower yield problem	0.2	0.0	0.5
Supply chain issues	0.2	0.0	0.5
4. Farmer acceptance	10.3	9.0	11.9
Lack of farmer acceptance	7.1	5.3	9.3
Lack of farmer knowledge and negative perceptions on OF	1.6	1.6	1.6
Need for increased farmer skills	1.1	1.6	0.5
Organic farming has a negative image	0.5	0.4	0.5
5. Other	9.8	8.2	11.9
Certification issues/monitoring	3.7	3.7	3.6
Fragmented industry	1.8	0.8	3.1
Property rights issues (contamination issues, gene transfer)	1.1	1.6	0.5
Land access/suitability of land for OF	0.7	0.8	0.5
Philosophical/religious/social factors	0.7	0.0	1.6
Public good aspect—inability to capture full benefits of OF	0.5	0.8	0.0
OF as a new scientific paradigm	0.2	0.0	0.5
Globalization issues	0.2	0.0	0.5
Negative media portrayal of OF	0.2	0.0	0.5
Refusal of banks to lend money for OF	0.2	0.4	0.0
Externality issue problem for OF from other farms	0.2	0.0	0.5
OF will not feed the world	0.2	0.0	0.5

Statistical significance comparisons are only made between major barrier categories, not between sub-headings.
*** Significantly different from general sample at 1% level with a two tailed *t*-test.
* Significantly different from general sample at 10% level with a two tailed *t*-test.

Table 2. Barriers named by professionals towards further adoption of genetic engineering.

Barriers	Total % ($n = 185$)	General sample % ($n = 119$)	Targeted (OF experienced) % ($n = 66$)
1. Public attitudes and media influences	40.8	43.7	36.6*
Public perception	34.9	38.9	29.2
Media portrayal	4.4	4.4	4.3
Disinformation by lobby groups	1.5	0.4	3.1
2. Scientific research issues	25.4	22.3	29.8
Lack of scientific research	10.5	10.0	11.2
Uncertainty of future effects	10.5	8.3	13.7
Communication of scientific info/scientists	1.5	1.7	1.2
Property right issues	1.3	0.9	1.9
Lack of independent verification	0.8	1.3	0.0
Misinformation about benefits from scientists and companies	0.5	0.0	1.2
Precautionary principle	0.3	0.0	0.6
3. Market issues	17.7	16.6	19.3
Overseas consumers concerns	9.0	12.2	4.3
Farmer acceptance	5.9	3.9	8.7
Losing markets	1.8	0.0	4.3
Marketing issues	0.8	0.0	1.9
Segregation issues	0.3	0.4	0.0
4. Costs of genetic engineering research	11.8	12.2	11.2
Political restrictions	6.7	7.4	5.6
Research costs	4.9	4.8	5.0
Low return on research and development	0.3	0.0	0.6
5. Other	4.4	5.2	3.1
Multinational company control	1.5	1.7	1.2
Environmental issues	1.3	1.7	0.6
Ethical concerns	1.3	1.2	1.2
Vested interests	0.3	0.4	0.0

Statistical significance comparisons are only made between major barrier categories, not between sub-headings.
* Significantly different from general sample at 10% level with a two tailed *t*-test.

'Australian certification agencies are completely pathetic on extension and they cannot get it together to be a proper force in influencing government'.
'I have wanted to do some organic research. I once offered my services (free of charge) to members in the organic industry—they declined, and did not want to know about it ... So what does that tell you about the industry?'

A few respondents did not believe there were any barriers to the further adoption of organic farming. One such respondent said:

'There seem to be no barriers large enough to prevent the adoption of organic agriculture in Australia. Farmers are taking it up like lemmings—and you know what happens to lemmings ...'

Others worried about what the consequences of increased adoption of organic farming may mean for its integrity:

'I have got reservations about organic agriculture becoming institutionalised or more mainstream—the more generalised advice that is offered then the more chance of this occurring'.

Beliefs about barriers to the further diffusion of genetic engineering

Some of the commonly cited barriers to the further diffusion of genetic engineering in Australia included: public attitudes and media influences, scientific research issues, market issues and actual costs of the research. Overall, there was virtually no significant difference between the targeted versus general samples in the barriers they perceived genetic engineering faced to further adoption in Australia; hence no differentiation between samples is commented upon.

The 'lack of consumer knowledge' and their negative attitude towards genetic engineering was one of the most cited barriers to the further diffusion of biotechnology. Consumers were viewed as not understanding the complexity of genetic engineering, and because of this lack of understanding, tended to reject the technology. For example:

'The public perceive biotechnology as a snake oil issue. The public has a fundamental lack of understanding of biotechnology'.

'It is just a number of vocal luddites that spread fear of the unknown to the public'.

Many professionals (in both the targeted and general samples) named the media as the key reason to why the public had such a negative attitude towards the technology. They believed that the media's portrayal was often inaccurate and biased against genetic engineering in general. Professionals would often cite the need for increased education of consumers to overcome the media's portrayal and to change how consumers viewed genetic engineering. For example:

'We need increased education of the public regarding biotechnology to achieve more acceptance. At the moment there is scaremongering and misinformation and the public do not understand the technology's benefits. We need to decrease the emotional element, and provide non-biased information. However, a lot of scientists are not willing to get involved in the public debate'.
'There is too much bias—for either organic agriculture or biotechnology. Too much sensational reporting for either goes on ... We need to have more unbiased, independent, balanced comment on the benefits and costs of both...'.

On the other hand, some of the respondents who named public attitudes as a barrier to further genetic engineering diffusion considered this as a good thing (generally these professionals viewed genetic engineering negatively overall). These professionals questioned the conventional scientific view of the role of education in changing consumers' views and the general perception by science that consumers are ill-informed. One such response was:

'It seems that the government believes that once people understand biotechnology more then they will accept it. But I do not understand this reasoning—I am an informed and knowledgeable scientist and I have discriminately used the technology, yet I remain sceptical about it'.
'Far from them being ignorant or ill-informed, the cautious approach in the farming community shows that they have very in-depth knowledge and understand the economic risks of biotechnology ... Therefore, increased education will not necessarily help them to understand biotechnology benefits, it may lead to a more positive view but it may as equally lead to a more negative view'.

The next largest barrier named against the further diffusion of genetic engineering in Australia was scientific research issues, that is, a supply constraint. A number of professionals believed that the lack of long-term research into the technology and the uncertainty and lack of transparency surrounding much of the current research was a detriment to the further adoption of the technology. Some believed that further long-term research would mean greater certainty and reassurance about the technology's net benefits and hence lead to greater adoption. For example:

'There is a lack of proof by biotechnology companies on the benefits of biotech products'.

'There is a lack of scientific data on the technology, which has led to uncertainty about future benefits and costs. The public is very mistrusting of government policy because of this lack of information'.

The third most named barrier facing genetic engineering was market issues, a demand constraint, and one similar to the first named barrier. Some professionals believed that genetic engineering crops in Australia would prove not to have enough economic benefits because many of Australia's key export markets (such as Japan and Europe) had effectively banned imports of genetically engineered products. Others believed that segregation issues (such as ensuring the separation of genetically engineered canola from other crops) would prove to be uneconomic for farmer adoption. The fourth most named barrier was to do with the actual cost of genetic engineering research. Many professionals believed that the costs of genetic engineering research were very high, the returns low, and that political restrictions made it uneconomic. Finally, a small number of professionals named ethical and environmental restrictions as barriers facing further diffusion of genetic engineering in Australia.

Information sources cited for organic farming

The previous sections have shown that professionals from the targeted and general samples named different barriers facing the further adoption of organic farming in Australia. It is therefore interesting to know whether they also named different information sources on organic farming. Table 3 illustrates the three main sources of information on organic farming named by Australian agricultural professionals.

There is a clear difference between the information sources used by general respondents and the information sources used by targeted respondents. General respondents consistently named the media/internet as their main source of information on organic farming, followed by scientific sources. Targeted respondents named the organic industry, scientific sources and organic farms/farmers as their main sources of information.

Information sources cited for genetic engineering

Table 4 illustrates the three main sources of information on genetic engineering named by Australian agricultural professionals.

Unlike the results for organic farming, there is little significant difference between the information sources used by general and targeted respondents on genetic engineering. Both samples consistently named scientific sources and the media/internet as their main source of information on genetic engineering, followed by peers. Although targeted respondents were more likely to name government and

Table 3. Information sources named by professionals on organic farming.

Information sources	Total % ($n = 185$)	General sample % ($n = 119$)	Targeted (OF experienced) % ($n = 66$)
First main source of information			
Media/internet	27.1	36.7	9.8***
Scientific sources	27.1	26.6	27.9
Organic industry	18.8	10.0	34.4***
Organic farms/farmers	14.7	15.6	13.1
Peers	12.4	11.0	14.8
Second main source of information			
Scientific sources	28.9	23.8	35.5***
Media/internet	22.5	26.3	17.7***
Peers	21.8	22.5	21.0
Organic industry	14.8	13.8	16.1
Organic farms/farmers	12.0	13.8	9.7
All other cited main sources of information			
Scientific sources	28.8	33.3	25.0**
Media/internet	26.3	27.8	25.0
Organic farms/farmers	20.0	8.3	29.5***
Peers	16.3	16.7	15.9
Organic industry	8.8	13.9	4.5***

*** Significantly different from general sample at 1% level with a two tailed *t*-test.
** Significantly different from general sample at 5% level with a two tailed *t*-test.

farms/farmers as a source of information than general respondents, the actual difference was small.

Discussion

Although agricultural professionals named demand constraints (i.e. small markets, the lack of consumer willingness to pay and consumers' negative attitudes) as the largest barrier facing further diffusion of organic farming or genetic engineering in Australia, there was a significant difference between the total amount of demand and supply constraints named for each innovation. Overall, 59% of professionals in the total sample named demand constraints facing further adoption of genetic engineering, while only 27% of professionals named demand constraints facing organic agriculture. In particular, targeted respondents (who on average were more knowledgeable about organic agriculture) were more likely to name supply constraints as their first largest barrier to further adoption of organic farming. Information needs by farmers and government support for organic farming (usually in the form of providing extension support or R&D) were seen by many as the greatest barrier to further diffusion of organic farming. In this regard, responses by targeted professionals were very similar to survey responses by organic farmers on their perceptions of the largest barriers to further adoption of organic farming.

Professionals' responses in naming a 'lack of consumer knowledge' and media portrayal of genetic engineering are also similar to the common response by the scientific community. Many scientists argue that the public does not understand genetic engineering and that consumers' reluctance to accept biotechnology therefore stems from ignorance and not wisdom. However, as mentioned previously, consumer research does not support this theory that more knowledge will lead to more acceptance[18,19]. Wheeler[27] investigated the role of knowledge in influencing agricultural professionals beliefs towards genetic engineering, and concluded that there was no evidence to suggest that increased knowledge of professionals led to a more positive overall view. Both opponents and proponents of the technology rated their knowledge similarly. On the other hand, it was found in Wheeler[26] that an increase in professional knowledge about organic farming did lead to a more positive view about the innovation. All these results suggest that the link between knowledge and acceptance of an innovation is complex, and requires future research.

As mentioned previously, the media is often perceived as misinforming the public on biotechnology and sensationalizing its issues[28]. However, it seems that the role of the media in influencing public opinion through negative stories has been overstated somewhat, as studies have shown that genetic engineering stories in the Australian media have been generally positive (55–70%), 17–32% have been neutral, and only 13–16% were negative[29,30]. Indeed, agricultural professionals themselves consistently named the media and internet as a main source of information on genetic engineering, and respondents from the general sample cited it even more strongly as an information source for organic farming.

Table 4. Information sources named by professionals on genetic engineering.

Information sources	Total % ($n = 185$)	General sample % ($n = 119$)	Targeted (OF experienced) % ($n = 66$)
First main source of information			
Scientific sources	35.7	39.5	28.8
Media/Internet	35.1	37.0	31.8
Peers	21.6	20.2	24.2
Government	4.3	1.7	9.1***
Farmers	2.7	0.8	6.1**
Industry	0.5	0.8	0.0
Second main source of information			
Scientific sources	38.6	37.5	40.3
Peers	32.9	35.4	29.0
Media/Internet	17.7	20.8	12.9
Government	7.6	3.1	14.5***
Farmers	1.9	2.1	1.6
Industry	1.3	1.0	1.6
All other cited main sources of information			
Scientific sources	29.5	25.0	33.3***
Media/Internet	29.5	36.4	23.5
Peers	22.1	29.5	15.7
Government	8.4	2.3	13.7***
Industry	6.3	6.8	5.9
Farmers	4.2	0.0	7.8***

*** Significantly different from general sample at 1% level with a two tailed *t*-test.
** Significantly different from general sample at 5% level with a two tailed *t*-test.

The other main perceived supply constraint against further diffusion of organic farming was seen to be on-farm issues (such as economic issues, pest and disease problems), although again, the more knowledgeable targeted sample were far less likely to see that as a barrier to further adoption of organic farming than the general sample. Respondents from the general sample generally saw on-farm and market issues as the key barriers to further diffusion, while professionals from the targeted sample generally saw information needs and government support as the key issue, but were also more likely to name farmer acceptance difficulties (changing mindsets) and other issues (such as certification difficulties, externality problems from conventional farms, etc.) as barriers.

In brief, the targeted sample seemed much more familiar with the actual practice and reality of organic farming than the general sample, and hence also tended to dismiss what is commonly perceived in the scientific community as organic farming's major problems. Wheeler[25] provides more background and detail on what professionals actually perceived as the major benefits and costs of each farming innovation. Responses from the targeted sample about the ranking of barriers facing future adoption of organic farming were consistently extremely similar to responses from previous organic farmer surveys. One reason for this similarity is that respondents from the targeted sample were much more likely to rely on the organic industry and organic farms/farmers as information sources than general respondents. This may reflect either that targeted professionals have difficulty in obtaining relevant scientific evidence specific for Australian organic farming, or that they view organic farmers as being up to date with the latest research or issues surrounding organic farming as an innovation.

On the other hand, there was little difference in responses between the targeted and general samples towards the barriers towards further diffusion of genetic engineering, or in their named information sources on genetic engineering. Apart from demand constraints, many professionals named supply constraints such as the need for more research, the costs of the research, the return of the research, the transparency and lack of independent verification of some of the research, and the political restrictions on research as major barriers against further diffusion.

Conclusion

There was a clear difference between the views towards organic farming of the targeted and general samples of agricultural professionals. The general sample was much more likely to name market issues and on-farm difficulties as the main obstacle facing further adoption of organic farming. Agricultural professionals who were part of the more knowledgeable sample were more likely to have views similar to organic farmers; that is, information needs and a lack of government support are the main obstacles facing further diffusion of organic farming.

Respondents from the targeted sample were also much more likely to name the organic industry and organic farms/farmers as key information sources on organic farming, unlike respondents from the general sample. Overall, professionals believed that supply constraints were the largest reason limiting organic farming expansion while they were much more likely to name demand constraints (such as public attitudes) as the largest barrier to further diffusion of genetic engineering in Australia. As to be expected, there was no significant difference detected between the genetic engineering views of the two samples, nor in their stated information sources (apart from slightly more reliance on farmers and government from the targeted sample). Interestingly enough, agricultural professionals named scientific sources and the media/internet as their main information sources, although the media/internet has been constantly blamed as causing negative public perceptions of genetic engineering. The similarity between the views of the targeted agricultural professionals and organic farmers themselves lend support to farmers helping shape agricultural policy changes.

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Soil CO_2 respiration: Comparison of chemical titration, CO_2 IRGA analysis and the Solvita gel system

R.L. Haney[1,*], W.F. Brinton[2] and E. Evans[2]

[1]USDA-ARS, 808 E Blackland Rd, Temple, TX 76502 USA.
[2]Woods End Laboratories, Inc., 290 Belgrade Road, Mt Vernon, ME 04352, USA.
*Corresponding author: rhaney@spa.ars.usda.gov

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Abstract

The measurement of soil carbon dioxide respiration is a means to gauge biological soil fertility. Test methods for respiration employed in the laboratory vary somewhat, and to date the equipment and labor required have somewhat limited more widespread adoption of such methodologies. The purpose of this research is to compare the results of measured soil CO_2 respiration using three methods: (1) titration method; (2) infrared gas analysis (IRGA); and (3) the Solvita gel system for soil CO_2 analysis. We acquired 36 soil samples from across the USA for comparison, which ranged in pH from 4.5 to 8.5, organic C from 0.8 to 4.6% and the clay content from 6 to 62%. All three methods were highly correlated with each other after 24-h of incubation (titration and Solvita $r^2 = 0.82$, respirometer and Solvita $r^2 = 0.79$ and titration versus respirometer $r^2 = 0.95$). The 24-h (1-day) CO_2 release from all three methods was also highly correlated to both basal soil respiration (7–28 days) and cumulative 28-day CO_2 respiration. An additional 24 soil samples were acquired and added to the original 36, for a total of 60 soil samples. These samples were used for calibration of the Solvita gel digital color reader results using CO_2-titration results and regression analysis. Regression analysis resulted in the equation $y = 20.6 * (\text{Solvita number}) - 16.5$ with an r^2 of 0.83. The data suggest that the Solvita gel system for soil CO_2 analysis could be a simple and easily used method to quantify soil microbial activity. Applications may also exist for the gel system for *in situ* measurements in surface gas chambers. Once standardized soil sampling and laboratory analysis protocols are established, the Solvita method could be easily adapted to commercial soil testing labs as an index of soil microbial activity.

Key words: chemical titration, soil CO_2 respiration, infrared gas analysis, soil microbial activity

Introduction

Soil respiration is an important aspect of soil-quality and an indicator of soil fertility[1]. As early as 1931, Smith and Humfeld[2] noted that during decomposition of green manures, the numbers of bacteria followed CO_2 evolution, which rose rapidly during the first 4 days and then declined to a fairly constant level. Even earlier, Gainey[3] noticed a parallel formation of CO_2, NH_4-N and NO_3-N in soil. In 1924, Lebedjantzev[4] stated that drying soil at low temperature appeared to increase the fertility of the soil which, he noticed, also occurred in nature. For roughly 90 years, CO_2 respiration from soil has been used as an indicator of the relative fertility of various soils[3–5]. Soil CO_2 respiration has been widely used for many years to quantify the impact on soil microbial activity of various treatment and management inputs. The purpose of many of these studies are mainly concerned with the rates of C, N or P mineralization in an effort to gain a clearer understanding of these natural processes. A clear understanding of nutrient cycling is essential to developing accurate computer models and could have a tremendous impact upon the soil testing industry.

Chemical titration for soil CO_2 respiration is an effective means whereby different soils can be compared for microbial activity. Soils are incubated along with an aqueous solution of KOH or NaOH in a small vial. The alkali reacts chemically with CO_2 and $BaCl_2$ and can be back-titrated with HCl to a phenolphthalein endpoint which is relative to the amount of CO_2 released by soil micro-organisms[6]. A control vial with no soil is included in the incubation to correct for the CO_2 in the jar at the initiation of the incubation. An equation is then employed to arrive at mg CO_2-C kg^{-1} soil. Soil CO_2 respiration can also be measured with a gas chromatograph or an infrared gas analyzer (IRGA) for CO_2 detector. Although chemical

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titration has avenues for error associated with the procedure, it is a fairly simple and straightforward method. However, the method requires mixing the alkali, assumption that the control is accurate, care in titration, and accurately hitting the endpoint, which can induce error.

More recently, soil laboratories have been reviewing early methods in view of environmental disposal concerns, such as in the use of dichromate for soil organic carbon digestion. The presence of $BaCl_2$ in the CO_2 titration procedure would qualify for such concern. To render unreacted $BaCl_2$ harmless after titration requires the additional step of adding an equimolar or greater amount of a soluble source of sulfate ions, producing insoluble $BaSO_4$. Such steps add to the complexity of the procedure.

The Solvita gel system was designed as a complete procedure to quantify the relative differences between varying types of compost in terms of the amount of CO_2 evolved in a short time period. This is interpreted as an indication of the completeness of active degradation, also called a maturity index[7]. In this research, a similar principle of CO_2 respiration is being applied to soil respiration. Soils differ from compost in that the gross amount of respiration is likely to be less than soils, since soils typically have 1/10th–1/20th the amount of carbon. The Solvita gel system is a new tool to evaluate soil microbial respiration rate in an efficient and cost-effective manner, without the need for reagent handling and standardization. A pH-sensitive gel (paddle) is embedded in a one-piece plastic holder that narrows to a point so that it can be pushed into the soil. After a specified time-period, the paddle can be removed from the incubation jar and analyzed with a digital color reader (DCR) developed specifically for the test. This process takes a minimum of time and labor. The USDA Soil Quality Institute has listed the Solvita kit as an alternate soil respiration procedure in its national soil-quality test kit program which released a full soil quality test document. This application of the Solvita gel-system was found suitable since it was able to detect meaningful changes in surface gas chambers CO_2 concentrations (John Doran, personal communication, October 2007). Solvita has been reported to have compared sensitivity to Dräger tubes when employed in compost chamber tests[8]. The Solvita chemistry gel technology is different from alkali traps in that it does not absorb all the CO_2 but absorbs a relative concentration of CO_2. Since its inception, the visual color strips used to interpret the reaction have been upgraded by the DCR in which the intensity of red, green and blue (RGB) emissions from the gel is read by a diode array detector (DAD) assembly within the DCR. Using this approach permits very rapid measurement of accumulated CO_2 within the Solvita gel at any time during incubation, and improves reliability and significantly increases accuracy. The reactive gel with DAD appears to closely obey Beer–Lambert's optical law over a wide range of concentration of CO_2 and suffers only small interference from volatile fatty acids which form a positive response with CO_2 gels, consistent with an unstable compost condition.

The Solvita system is almost error free, since it involves placing the paddle in the soil and removing it after the allotted time-period, placing it in the reader and pressing a button. Soil CO_2 respiration is a common and simple measure of biological activity in soil. Soil microbial activity as measured by CO_2 respiration is a function of substrate availability, which is related to the amount or quality of organic C and N. The purpose of this research is twofold: first, to compare the soil CO_2 release from the titration method, IRGA and the Solvita gel system, and secondly, to investigate the possibility that the release of CO_2 can be adapted to soil testing labs to provide a biological method that could discern differences in soil microbial activity which might provide an additional insight to the relative activity of different soils.

Materials and Methods

Experiment 1

Thirty-six soil samples were collected from Texas, Oklahoma, Georgia, Mississippi, Idaho, Wyoming and Illinois. The range in soil pH was 5.0–8.3, soil organic C 0.65–4.52%, and clay content 10–55%. All soils were ground to pass a 5-mm sieve, dried at 40°C and weighed into 50 ml plastic beakers. All soils were wetted to approximately 50% water-filled pore space.

Titration. Forty grams of wetted soil was placed in a 1 pint mason jar along with a vial of 10 ml of 1 M KOH. The alkali traps were changed and titrated at days 1, 3, 7, 14, 21 and 28. Unreacted alkali in the KOH traps was back-titrated with 1 N HCl to determine CO_2-C[6]. Basal soil respiration was calculated by subtracting the cumulative 7-day CO_2-C from the cumulative 28-day CO_2-C.

IRGA. Forty grams of wetted soil samples were placed in 8 oz jars and capped. Each jar was connected to the IRGA via twin solenoids which open simultaneously to allow CO_2-free air to purge the jar of CO_2 and direct it to the analyzer (ADC model 225) at a rate of 400 ml min^{-1} for 3 min. Eight soil samples and two controls were used in the 10 sample system. Each glass jar was sampled for 3 min and then closed (Fig. 1). The samples were analyzed every hour for 24 h.

Solvita. Forty grams of wetted soil samples were placed in 8 oz glass jars with a Solvita gel paddle. At the end of 24 h each paddle was placed in the DCR for analysis (Fig. 2). A simple regression analysis was used to assess the correlation between 24-h CO_2 evolution from titration versus the Solvita gel and CO_2-C from IRGA.

Experiment 2

An additional 24 soil samples from Utah, Washington, California, Montana, New Mexico, North Carolina, Maine, Pennsylvania and Ohio were acquired and added to the original 36 in dry form. All 60 samples were wetted as described above and incubated for 24 h. The titration method and the Solvita gel system were used for 1-day

Figure 1. Closed system soil respirometer.

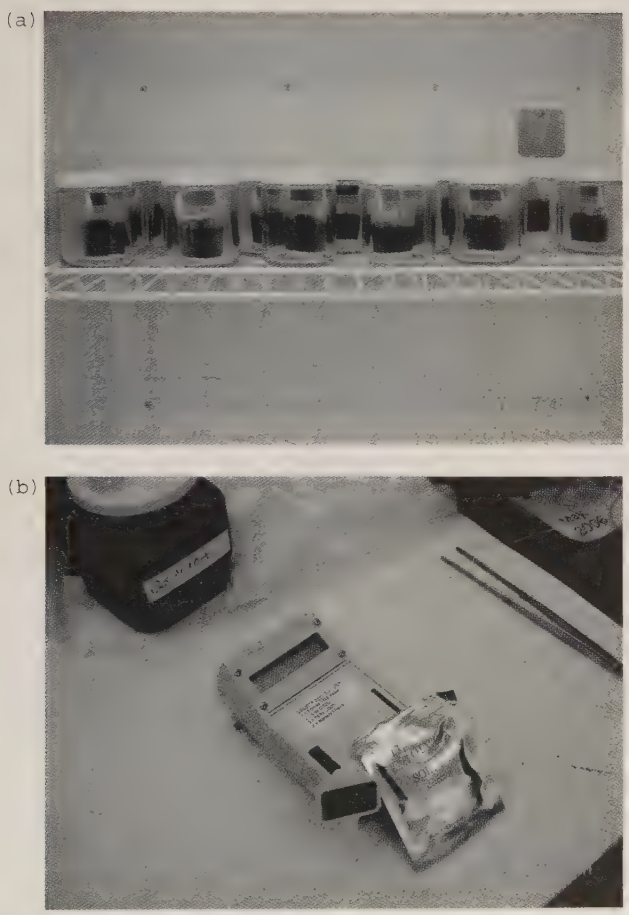

Figure 2. (a) Solvita gel paddles in soil and (b) Solvita digital reader.

CO_2-C analysis to calibrate the DCR to the CO_2-C from titration.

Experiment 3

Since the Solvita gel system does not absorb all the CO_2 within the container but rather absorbs a relative amount, we chose 20 soil subsamples to study the influence of container volume on CO_2 respiration by the Solvita gel system. Twenty grams of soil samples were weighed into 50 ml plastic beakers, rewetted as described above, and placed into 8, 16 and 32 oz glass jars with gel paddles in each jar. After 24 h of incubation the paddles were removed and analyzed with the DCR.

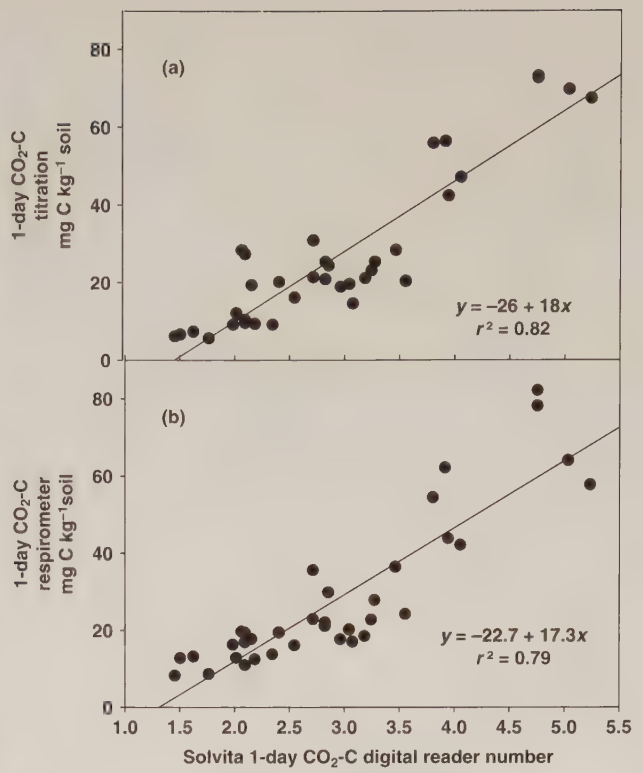

Figure 3. Solvita 24-h CO_2 versus (a) 24-h CO_2-C titration and (b) 24-h CO_2-C closed system respirometer.

Results and Discussion

Experiment 1

The Solvita number from the DCR was compared to the CO_2-C from both the titration method and the CO_2-C from the closed system respirometer (IRGA) glass after 24-h (1-day) incubation. Regression analysis established a highly significant relationship between CO_2 evolution from the Solvita number and titration ($r^2 = 0.82$, Fig. 3a) and the Solvita number and the CO_2-C from the respirometer ($r^2 = 0.79$, Fig. 3b). There was also a highly significant relationship between titration and the respirometer methods after a 24-h incubation ($r^2 = 0.95$, Fig. 4). The strong correlations between these methods suggest that any of the three methods could rapidly quantify soil microbial activity, although the Solvita method would be the simplest and least labor intensive. Since most of the 36 soils were in a dry state when they arrived at our lab, we chose to incubate the soils for 28 days after rewetting. We calculated basal soil respiration as the cumulative 28-day minus the

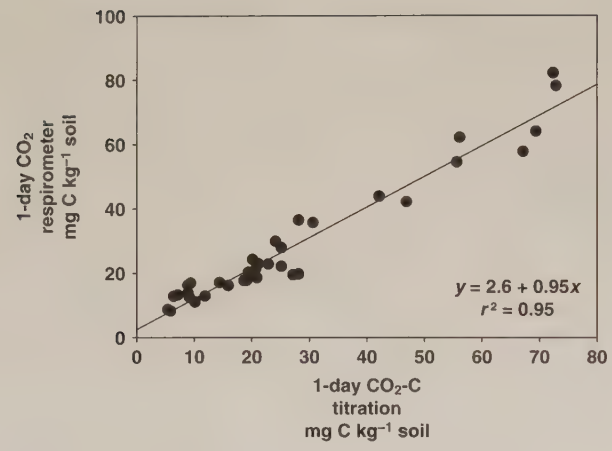

Figure 4. 24-h CO_2-C titration versus 24-h CO_2-C respirometer.

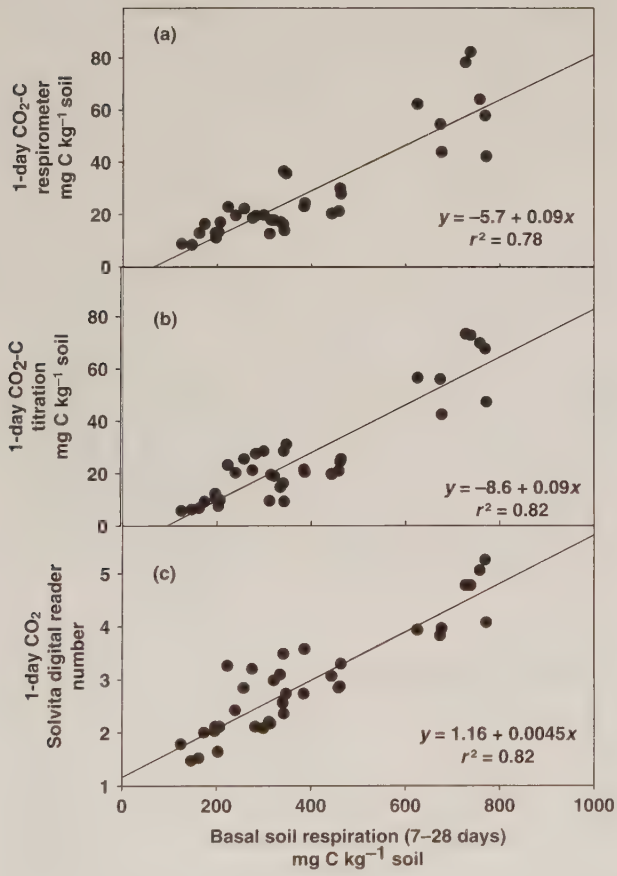
(a)
1-day CO2-C respirometer mg C kg−1 soil
y = −5.7 + 0.09x
r2 = 0.78
(b)
1-day CO2-C titration mg C kg−1 soil
y = −8.6 + 0.09x
r2 = 0.82
(c)
1-day CO2 Solvita digital reader number
y = 1.16 + 0.0045x
r2 = 0.82
Basal soil respiration (7–28 days) mg C kg−1 soil

Figure 5. Basal soil respiration (7–28 days cumulative) versus (a) 24-h CO_2-C closed system respirometer, (b) 24-h CO_2-C titration and (c) Solvita CO_2 digital reader number.

initial 7-day period for CO_2-C after rewetting. A paper by Franzluebbers[9] indicated that a 7-day incubation period was adequate to overcome the elevated release of CO_2-C from the drying–rewetting effect. Therefore, we compared basal soil respiration (7–28 days) against the 1-day CO_2 value from titration, respirometer, and Solvita to explore possible changes in microbial activity after removing the drying/rewetting flush of CO_2. The relationships of each 1-day

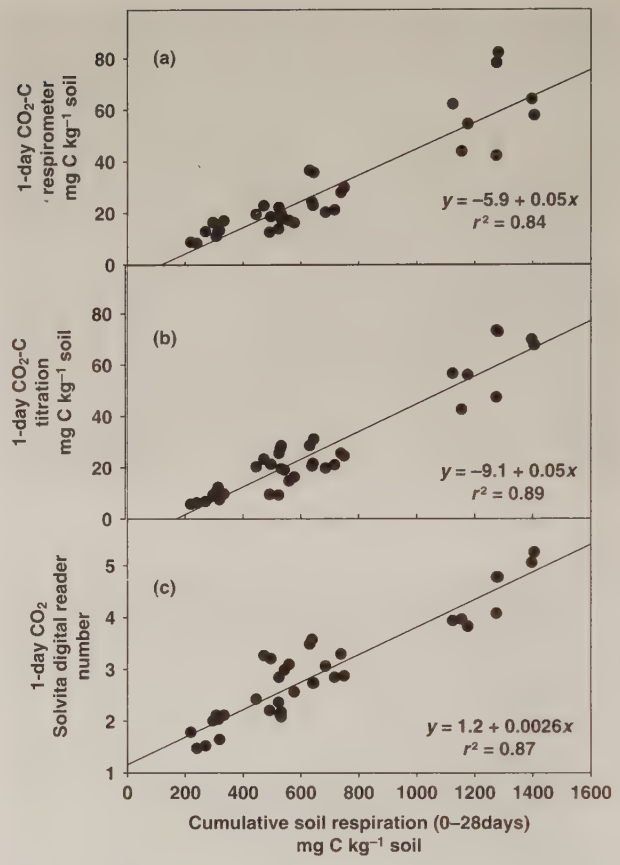
(a)
1-day CO2-C respirometer mg C kg−1 soil
y = −5.9 + 0.05x
r2 = 0.84
(b)
1-day CO2-C titration mg C kg−1 soil
y = −9.1 + 0.05x
r2 = 0.89
(c)
1-day CO2 Solvita digital reader number
y = 1.2 + 0.0026x
r2 = 0.87
Cumulative soil respiration (0–28days) mg C kg−1 soil

Figure 6. Cumulative soil respiration (0–28 days) versus (a) 24-h CO_2-C closed system respirometer, (b) 24-h CO_2-C titration and (c) Solvita CO_2 digital reader number.

method to basal soil respiration are shown in Figure 5. The respirometer data for 1 day had an $r^2 = 0.78$ (Fig. 5a), titration exhibited an $r^2 = 0.82$ (Fig. 5b), and Solvita an $r^2 = 0.82$ (Fig. 5c) with basal soil respiration. Again, each method proved to be adequate at predicting basal soil respiration even though the 1-day CO_2 release was taken during the greatest portion of the CO_2 release from the drying/rewetting process[10,11]. We also compared the 1-day CO_2 release after drying/rewetting with the cumulative 28-day CO_2 evolved including the flush of CO_2 from drying/rewetting. The relationships between 1-day CO_2 and 28-day CO_2 showed only slightly better correlations compared with 1-day CO_2 and the basal rate. The respirometer data had an $r^2 = 0.84$ (Fig. 6a), titration an $r^2 = 0.89$ (Fig. 6b), and Solvita an $r^2 = 0.87$ (Fig. 6c) with cumulative 28-day CO_2-C.

Experiment 2

The soil CO_2 released, after soil drying/rewetting and incubating for 24 h, from 60 soils was determined using the Solvita gel system with a DCR and was highly related to 24-h soil CO_2 measured using the titration method (Fig. 7). Although drying soil is not a prerequisite to using the system; we used dried soil to start all the soils in the experiment from an equal state. We also wanted to

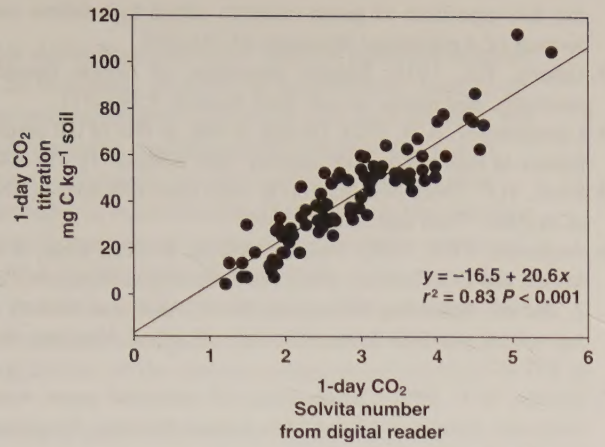

Figure 7. 1-day CO_2 Solvita versus 1-day CO_2 titration. Sixty soil samples from US, pH range 4.5–8.5, soil organic C range 0.8–4.6% clay content range 15–62%.

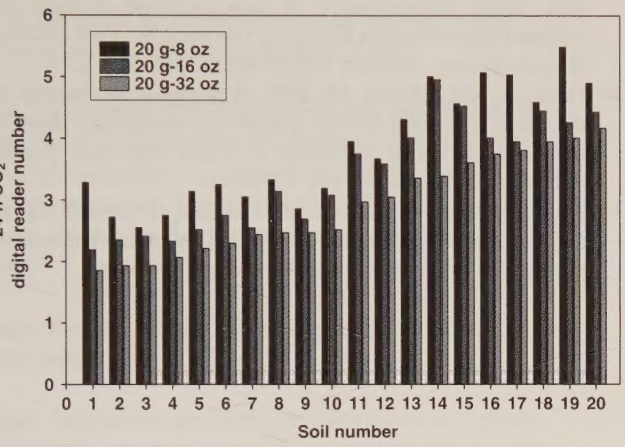

Figure 8. Influence of chamber volume on digital reader number. Twenty grams of soil subsamples were used for each chamber. Chamber size was 8, 16 and 32 oz.

accommodate soil testing protocols since most soil testing labs dry and grind their soil samples prior to analysis. The above-mentioned relationship suggests that the Solvita soil system can be equally as effective as the titration method as an index of microbial activity in order to quantify changes or differences in soil respiration from various soils. The equation $y = 20.6 * (\text{Solvita number}) - 16.5$ can be used to convert the DCR number to CO_2-C, which is commonly reported with the titration method (Fig. 7).

Experiment 3

When high soil CO_2 respiration is expected, it is possible to increase the container volume, which will dilute the relative amount of CO_2 in equilibrium with the gel. This provides flexibility to measure soils with recent manure or compost additions without overwhelming the system with carbon dioxide. The analogous limit with standard CO_2 titration methods is when the base (KOH or NaOH) becomes overwhelmed with excess carbonate, and the appropriate

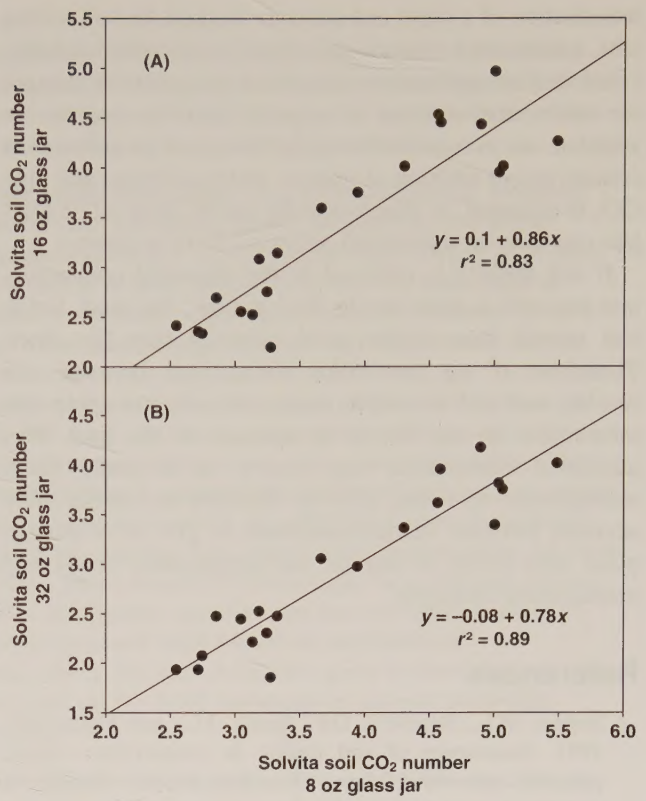
(A)
Solvita soil CO2 number 16 oz glass jar
y = 0.1 + 0.86x
r² = 0.83
(B)
Solvita soil CO2 number 32 oz glass jar
y = −0.08 + 0.78x
r² = 0.89
Solvita soil CO2 number 8 oz glass jar

Figure 9. Chamber volume relationships on soil CO_2.

recourse is to increase the amount of alkali, or raise its concentration. When we compared various volumes, the mean Solvita number across all 20 soils for the 8 oz jar was 3.84 with a standard deviation of 0.22, mean for the 16 oz jar was 3.40 with a standard deviation of 0.20 and the mean for the 32 oz jar was 2.91 with a standard deviation of 0.18 (Fig. 8). The linear regression relationships between chamber volumes are illustrated in Figure 9. Twenty soils samples of 20 g were used for each chamber volume. The 20 g soil 8 oz glass jar volume is compared to both the 16 and 32 oz glass jar volumes. The data indicate that it is feasible to use greater volumes to dilute the CO_2 when incubating soil samples that are expected to produce a high output of soil CO_2. We chose to use the 8 oz glass jar since it had the strongest relationship with CO_2 from both titration and IRGA compared to the 16 and 32 oz jars (data not shown).

Conclusion

The methods we compared were well correlated with each other and offer promise in utilizing soil CO_2 data as an index of microbial activity. However, a concentrated effort would be needed to further this research and develop a standardized method for microbial activity which could be readily adapted by soil testing labs. The Solvita gel measurement of soil CO_2 is a simple and rapid method which can quantify microbial activity from various soils. Since soil fertility is a relative estimate between soils, the

introduction of a rapid and accurate method for soil testing labs, which could separate soils based on microbial activity, could find an application in tracking management changes for either conventional or organic farming systems. In addition, we recommend using the 8 oz glass jar unless soils contain recent addition of manure and/or compost and high CO_2 is expected, in which case the use of 16 or 32 oz glass jars can then be substituted without loss of accuracy.

If soil fertility is reflected in the microbial community and one soil is more fertile than another, the more fertile soil should have higher yield potential than the other. Therefore, if we can make connections between soil fertility and soil microbial respiration, we can apply this information to our benefit as stewards of the land. This additional information may enable us to make better management decisions, give us direction in making more accurate fertilizer recommendations or give us a starting place with which to monitor our performance in our soil management strategies.

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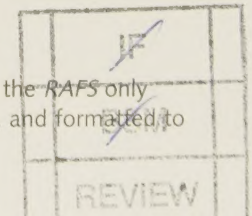

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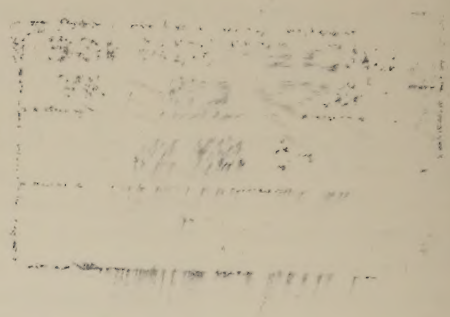

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